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Overview of Virtual Test Bed FY23 Activities

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National Reactor Innovation Center

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REVISION LOG

Revision No.	Date	Affected Pages	Description
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SUMMARY

This milestone report highlights progress achieved within the Virtual Test Bed (VTB) project during Fiscal Year (FY) 2023. The VTB consists of an open-source repository of state-of-the-art simulation examples for advanced reactor types. Its objective is to help accelerate reactor maturation and deployment by providing 'reference' models that can be openly accessed, improved upon, and re-purposed for proprietary applications. The main accomplishments are summarized below:

1. Models on the repository were consistently maintained and new improvements were developed to improve the useability of the website. These new improvements include a tagging system and testing of computationally expensive models.
2. A total of 19 new models were uploaded to the repository this FY. They showcase a wide range of new modeling and simulation capabilities for advanced reactors. The VTB website also now contains two tutorials/trainings with two additional ones coming soon.
3. Model development activities were focused this FY on potential use cases for demonstration within the NRIC test beds. The DOME use case was a gas-cooled microreactor, and the LOTUS use case was a molten salt reactor. The models developed as part of this scope are expected to help provide the foundation for potential confirmatory analyses in the future, thus accelerating potential timelines for reactor deployments.

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ACKNOWLEDGEMENTS

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CONTENTS

FIGURES

TABLES

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ACRONYMS

ANL	Argonne National Laboratory
ANS	American Nuclear Society
ART	Advanced Reactor Technology
CFD	Computational Fluid Dynamics
DOE	U. S. Department of Energy
DOME	Demonstration of Microreactor Experiments
EBR-II	Experimental Breeder Reactor-II
FHR	Fluoride High-Temperature Reactor
FY	Fiscal Year
GPBR	Generic Pebble Bed Reactor
HPC	High-Performance Computing
HTGR	High Temperature Gas Cooled Reactor
HTTF	High Temperature Test Facility
INL	Idaho National Laboratory
LEU	low enriched uranium
LMFR	Liquid Metal Fast Reactors
LOFA	Loss of Flow Accident
LOTUS	Laboratory for Operation and Testing in the United States
LWR	Light Water Reactor
M&S	Modeling and Simulation
MCRE	Molten Chloride Reactor Experiment
MHTGR	Modular High-Temperature Gas Reactor
MOOSE	Multiphysics Object-Oriented Simulation Environment
MSFR	Molten Salt Fast Reactor
MSR	Molten Salt Reactor
MSRE	Molten Salt Reactor Experiment
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NRIC	National Reactor Innovation Center
NTP	Nuclear Thermal Propulsion
PBMR	Pebble Bed Modular Reactor
SAM	System Analysis Module
SNAP8	Systems for Nuclear Auxiliary Power 8
THM	Thermal Hydraulics Model
TREAT	Transient Reactor Test Facility
VTB	Virtual Test Bed
VTR	Versatile Test Reactor

1. BACKGROUND AND OVERVIEW

The National Reactor Innovation Center (NRIC) was created for accelerating the deployment of novel reactor concepts. This will be achieved by providing both physical and virtual spaces for building and testing various components, systems, and complete pilot plants. The Virtual Test Bed (VTB) represents the virtual arm. It is being developed in collaboration with U.S. Department of Energy's (DOE) Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.

The mission of the VTB is to accelerate the deployment of advanced reactors by facilitating the leveraging of cutting-edge DOE advanced modeling and simulation (M&S) tools to design, evaluate, and license reactors. This is primarily achieved by storing example challenge problems in an externally available repository and by developing models to fill the potential demonstrator's M&S gaps.

Activities conducted this fiscal year (FY) within the Idaho National Laboratory (INL) workscope centered around three key areas: (1) repository maintenance and improvement, (2) hosting external models to the repository, and (3) developing additional modeling examples relevant to potential demonstrators. The main accomplishments in FY23 included:

- Scope #1, Repository:
  - Continued identifying and resolving deprecations in the models and codes as new updates were pushed.
  - Set up template and format for new model submission.
  - Development of "model filter" capability to more easily search the ever-growing list of models on the repository.
  - Set-up HPC-link to enable testing of more computationally demanding models
- Scope #2, External Models:
  - Addition of 19 new models developed by other programs (DOE NEAMS, Advanced Reactor Technology [ART], U.S. Nuclear Regulatory Commission, etc.) to the VTB repository.
  - Notable novel capabilities include: multiphysics models for gas and heat pipe-cooled microreactors, a fuel performance model, and structural deformation models.
  - The VTB hosts an increasing number of 'tutorials' to help initiate users on the capabilities hosted on the VTB. This includes two existing tutorials on the MultiApp system and the Workbench interfaces. Two additional tutorials are currently under preparation: a thermal hydraulics tutorial for pebble bed reactors, and fuel performance modeling for a wide range of reactor types.
- Scope #3, New Models:
  - Development of an example use case for the NRIC 'DOME' testbed: gas-cooled microreactor.
  - Development of an example use case for the 'LOTUS' testbed: low-power molten salt reactor.

2. REPOSITORY MAINTENANCE AND IMPROVEMENT

2.1 Repository Status And Maintenance

The first major change in FY23 concerns testing practices. Regression testing was extended across all the previously added VTB models, aside from the most computationally expensive models which would require large “gold” files that act as reference solutions to be stored for comparison. New models were all accepted into the repository with both syntax checks and regression testing. The extension of regression testing to past models found issues with a restart configuration for a PBMR400 neutronics input. This issue is in the process of being resolved with work ongoing in the MOOSE software to transform the restart and recover system.

Over 40 pull requests were made to the repository to update the models, remove deprecation and adapt to new syntaxes. Most of these updates were performed by the developers of the NEAMS codes, and a little under half by the VTB technical staff. Issues fixed by VTB personnel were usually discovered or fixed during scheduled codes updates, while issues fixed by code developers were discovered through the automatic testing of the VTB models performed when modifying the codes.

The current testing status of the VTB is shown in Figure 1. Most codes fully past the test suite for the models they are supposed to run. The combined applications, BlueCrab and Direwolf, fail a few tests each. The Direwolf failures are currently due to unused parameters in the inputs and the executable inexplicably failing to allow it. One BlueCrab failure is tied to the restart/recover issue previously mentioned. Three pull requests are open in the repository. One attempts to improve the performance of an microreactor model steady-state calculation; it currently requires further attention. Another uses the new general field transfer technology, developed by NEAMS in FY23, in all the inputs across the repository.

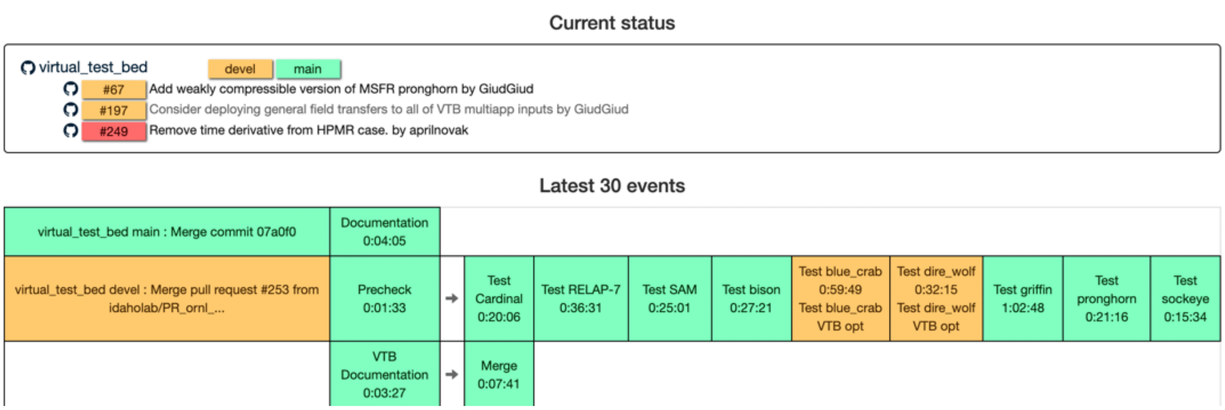


Figure 1. Current status of the VTB testing on the continuous integration platform.

To better assess the impact of the VTB, utilization by internal and external collaborators should be tracked. Github offers an interface that tracks both website traffic and “forking”, the act of creating an independent copy of the VTB. Github reports 32 active forks of the repository over the last year. Figure 2 indicates that between the last week of June and first week of July 2023, 50 unique visitors have browsed through the repository. To confirm these numbers, an additional usage tracking mechanism using Google Analytics was implemented. This was set up at the beginning of April. This data is presented in Figure 3. Over this period, nearly 600 unique visitors have browsed the repository, with 465 located in the United States.

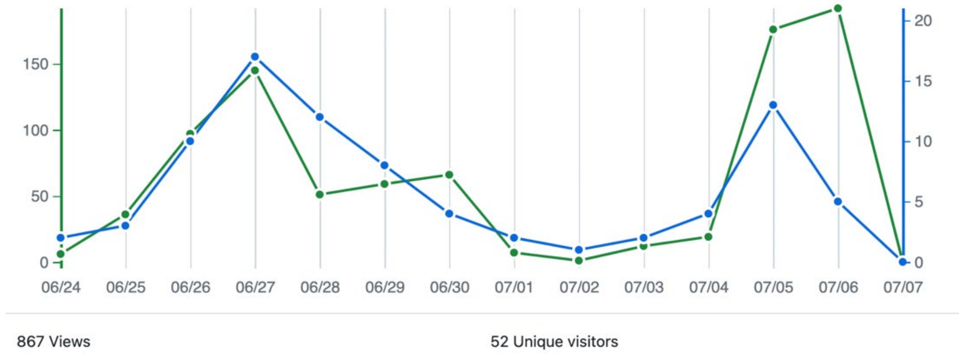


Figure 2. Repository visits tracking over June 24 – July 7 using the GitHub activity page.

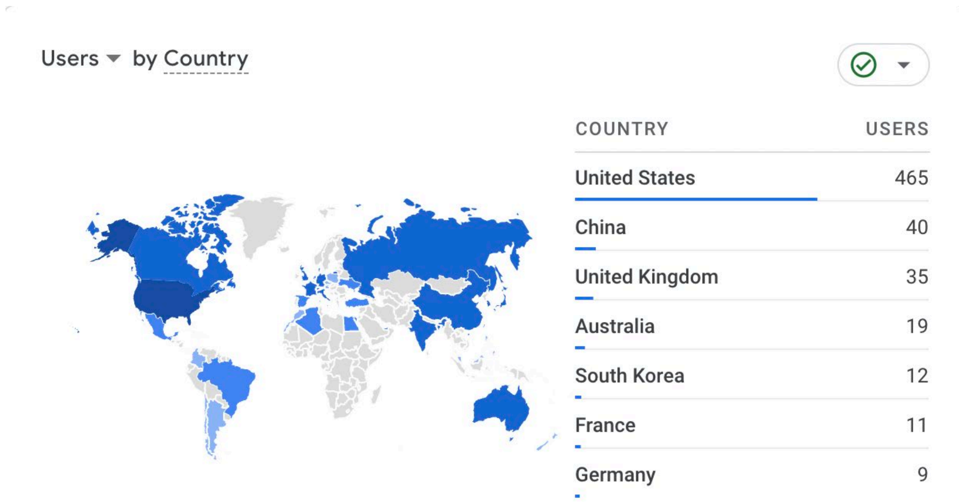


Figure 3. Usage tracking using Google Analytics over May 1 - July 6.

The documentation of the VTB models was modified through 14 pull requests, which notably added direct links from documentation to models, highlighted the open-source models in the model indexing, added instructions to download mesh files for some large models, added some missing citations for models that were unpublished at the time of release, and kept the model indexing up to date. Four pull requests were made by model points of contact to improve the documentation of the model.

2.2 Repository Improvements

Now at more than 30 models, as the repository grows it becomes more and more challenging to search for an input containing a feature of interest, a specified level of fidelity, a specific physics solve, etc. To enable these searches, which are primordial to using the VTB as an example before building a new model, several indexes of the models were created manually, sorted and linked from the front page:

- By reactor type
- By code used, with a special category for fully & partially open-source models
- By features present

- By computing needs.

This manual sorting is labor-intensive and prone to becoming outdated. Two new capabilities were developed for MooseDocs (the markdown language used to write documentation for MOOSE) to handle this automatically. A tagging command was written to aid in the filtering of models. This command allows the author of a model to supply a set of key value pairs to a dictionary which can then be used to filter down to a specific simulation. The command also supplies a path to the directory of the tagged markdown in the dictionary. This path can then be used to link to the corresponding simulation. For example, the High Temperature Gas Reactor (HTGR)assembly Multiphysics simulation could be tagged within its markdown file as:

```
!tagger HTGR_Assembly_mps simulation_type:steady_state reactor:generic_HTGR
```

This would allow users to filter models by simulation type and multiphysics calculation and provide the user with a link to the documentation to the resulting HTGR model.

The tagging command line below would allow users to filter to the Molten Salt Fast Reactor core transient model documentation.

```
!tagger MSFR simulation_type:transient reactor:MSFR
```

The second facet of this is a simple web API (application programming interface) that parses the dictionary and provides a search feature. Because all MOOSE websites are static, out of cyber security concerns, the search code is executed on the visitor's browser. The search page currently has a limited interface, shown in Figure 4.

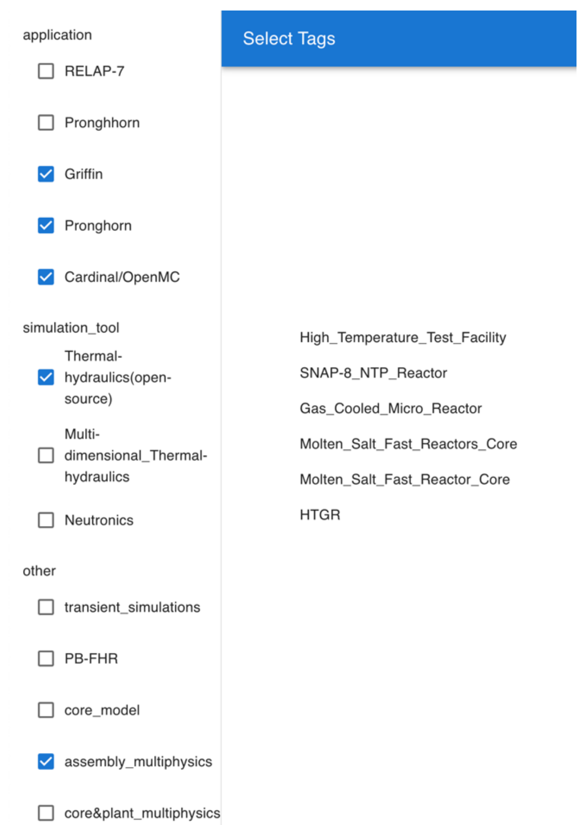


Figure 4. Current prototype status of the search feature. This is being expanded to capture all models on the VTB currently.

A template format was also added for the submission of new models to the VTB by Jun. Fang at Argonne National Laboratory (ANL). This streamlines the process and avoids major misses in new submissions. It also facilitates the review of new models. The minimal submission is guided to include:

- A description of the reactor with some graphical description and historical context
- A description of the inputs starting from the general design concepts, then diving into the roles of the individual objects in the simulation
- A description of the results and their significance
- How to run the model, notably on INL High-Performance Computing (HPC) infrastructure.

It also acts as a targeted tutorial to MooseDocs, the markdown language used to write documentation for MOOSE, presenting examples on how to create tables, figures, paragraphs and so on. In that regard, it is inspired by the American Nuclear Society's (ANS) templates for conference presentation summaries.

The VTB also began deployment of HPC enabled testing in FY23. The list of models that can only be run using an HPC cluster is identified already in a specific indexing of the VTB. Most models in this category are using Nek, the ANL-developed Computational Fluid Dynamics (CFD) solver. High fidelity CFD simulations require very fine mesh and are often run on Graphics Processing Units (GPUs) or large groups of Central Processing Units (CPU). Some other computationally intensive models are full core heterogeneous multiphysics models, such as the heat pipe microreactor core transient models. A script was designed to run these cases manually in an interactive session with four cluster nodes mobilized. The codes are built manually from source beforehand. The results are then checked by the script.

A more automated continuous integration solution to HPC model testing is currently facing the four following challenges:

1. Automatic testing on the HPC requires building the code on one of the "head" (main) nodes, as the codes cannot currently be built without internet access. This is a resource-intensive activity and the head nodes are already significantly overused. The file system slowness is a regular complaint from HPC users and building the entire suite of NEAMS tools regularly would only aggravate the problem.
2. It also requires administrative privileges for the CIVET client hosted on HPC. This level of permission requires great care with little tolerance for mistakes in the setup; the login node could be brought offline (for all HPC users) in the case of any incorrect manipulations. It is typically only granted to HPC staff.
3. The VTB is hosted on a public github repository. The combination of this fact and the administrative rights could enable, in theory, a pathway for cyber-attackers to gain control of an INL HPC cluster. In practice, external contributors have to be added manually to an "allow"-list before any traffic from their code to CIVET is even allowed.
4. Current deployment work in the MOOSE team will remove these three limitations in the near future with the deployment of pre-built containerized software solutions. It is considered more strategic to leverage these ongoing activities than work on solutions to each limitation. They are expected to be completed prior to the end of this FY.

3. HOSTING EXTERNAL REACTOR MODELS

An overview of the models currently hosted is provided in Table 1. The Table showcases the breadth of reactor types and analysis tools showcased within the repository. The intent is for users to "mix-and-match" different combinations of use cases to suit their particular needs. New models for FY23 are highlighted in blue.

Table 1. Overview of reactor models hosted on the VTB. New models uploaded in FY 23 are highlighted in blue.

Type	Reactor	Simulation	Codes Used
MSR	MSFR	Core neutronics and hydraulics, steady state + transient	Griffin; Pronghorn
		Core + system neutronics and hydraulics, steady state + transient	Griffin; Pronghorn; SAM
		Core depletion with species removal	Griffin
		Core high-fidelity CFD (LES and RANS)	Nek5000
		Primary loop Transient	SAM
		Core steady state chemical species tracking + thermochemistry	Griffin; Pronghorn; Thermochimica
	MSRE	Primary loop steady-state and transient	SAM
		Core coarse-mesh steady-state and transient	Pronghorn; SAM
	LOTUS	Molten salt reactor core hydraulics and structure; steady-state and transient	Griffin; Pronghorn; Bison
HTGR	PBMR	Core neutronics and hydraulics, steady state + transient	Griffin; Pronghorn
		67 pebble high-fidelity conjugate heat transfer	Cardinal
		Primary loop steady-state and transient	SAM
	MHTGR	Primary loop steady-state	SAM
		Assembly high-fidelity neutronics and thermal hydraulics	Cardinal
		TRISO fuel performance	Bison
		Core neutronics steady-state	Griffin
	HTTF	Hydraulics and structure transient	RELAP7/THM
		Hydraulics system steady-state and transient benchmark	SAM
		High-fidelity CFD of lower plenum	Nek5000
	HTR10	Core neutronics steady-state	Griffin
	TREAT	Core pulsed transient	Griffin; Bison
FHR	Mk1	Core neutronics and hydraulics, steady state	Griffin; Pronghorn
		Reactor bypass high-fidelity conjugate heat transfer	Cardinal
		Primary loop steady-state and transient	SAM
		Core + system neutronics and hydraulics, steady state	Griffin; Pronghorn; SAM
	gFHR	Equilibrium pebble core with neutronics and hydraulics	Griffin; Pronghorn
LMFR	Lattice	Assembly neutronics, hydraulics, and fuel	Griffin; SAM; Bison
		Sub-channel hydraulics benchmark	Pronghorn

Table 1. (continued).

Type	Reactor	Simulation	Codes Used
		Lead-cooled reactor assembly heterogeneous neutronics	Griffin
		Duct bowing	MOOSE/Thermo-mechanics
	VTR	3D Core neutronics, hydraulics, and fuel; steady-state	Griffin; SAM; Bison
	ABTR	Primary loop Transient	SAM
Micro	Heat pipe	Core hydraulics and structure, steady-state	Sockeye; Bison
		3D Core neutronics, hydraulics, and fuel; steady-state and transient	Griffin; Sockeye; Bison
		3D Core neutronics, hydraulics, and fuel with hydride migration; steady-state and transient	Griffin; Sockeye; Bison
	Gas cooled	Assembly neutronics, hydraulics, and structure; steady-state and transient	Griffin; SAM; Bison
		System steady-state and transient	MOOSE/Thermal hydraulics
	SNAP8	2D Core neutronics and structure; steady-state	Griffin; Bison

As can be seen in Table 1, there were several new additions to the VTB repository this FY. All reactor types have nearly double the number of models from the previous year update, with new single and multiphysics analyses of steady state and transient scenarios. A summary of recently added models will be discussed in more detail in the following subsections. An overview of the models will also be presented at an ANS Winter Conference special session on the VTB.

3.1 Molten Salt Reactors (MSR)

The VTB hosts several example simulations for Molten Salt Reactors (MSRs). Two main design variants are represented, the fast spectrum MSFR, [1] and the thermal spectrum MSRE [2]. Additionally, a new model for the first MSR experiment to go into LOTUS was also developed and is discussed in more detail in Section 5.2.

3.1.1 Molten Salt Fast Reactor (MSFR)

While several models for the MSFR were already hosted in the VTB (see Table 1), including a Pronghorn-SAM model, a standalone 1D SAM model was recently uploaded to the VTB , and is showcased in Figure 5. This model demonstrates the point kinetics capabilities within the code to allow comparisons against the higher fidelity Griffin-Pronghorn-SAM model on the repository.

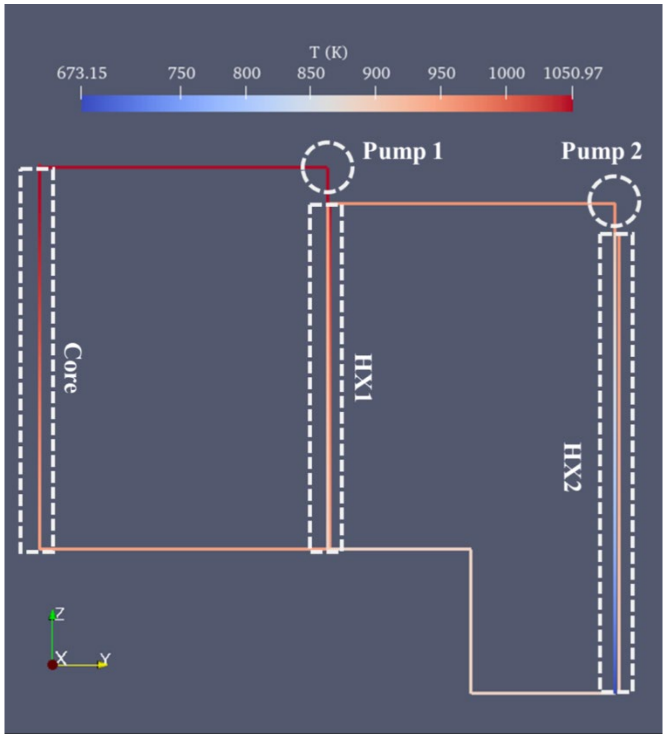


Figure 5. The steady-state temperature distribution in the 1D MSFR primary loop model using SAM.

Additionally, a new chemical species tracking and thermochemistry model of the MSFR was recently finalized. This model uses a steady state multiphysics solutions from Griffin and Pronghorn, and then solves the steady state thermochemistry of the MSFR system given the temperature, pressure, and elemental spatial distributions as seen in Figure 6.

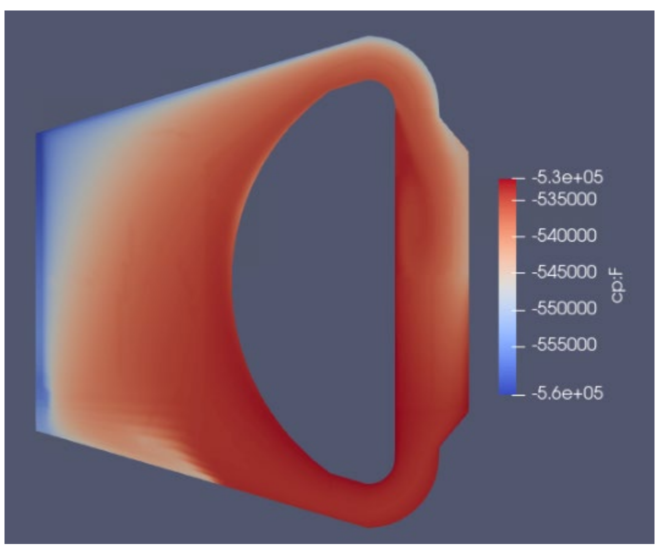


Figure 6. Steady state fluorine potential (J/mol) in the MSFR.

3.1.1.1 Molten Salt Reactor Experiment (MSRE)

A Pronghorn-SAM coupled model of the MSRE primary loop was developed and shown in Figure 7. Pronghorn was used for the reactor core and primary loop and was coupled to a SAM primary loop model using a "domain overlap" approach. The SAM model captures both the primary and secondary loop of the system. Future work intends to couple the Pronghorn model to Griffin in a similar fashion as the Pronghorn-Griffin-SAM model of the MSFR that was previously uploaded to the VTB. [1]

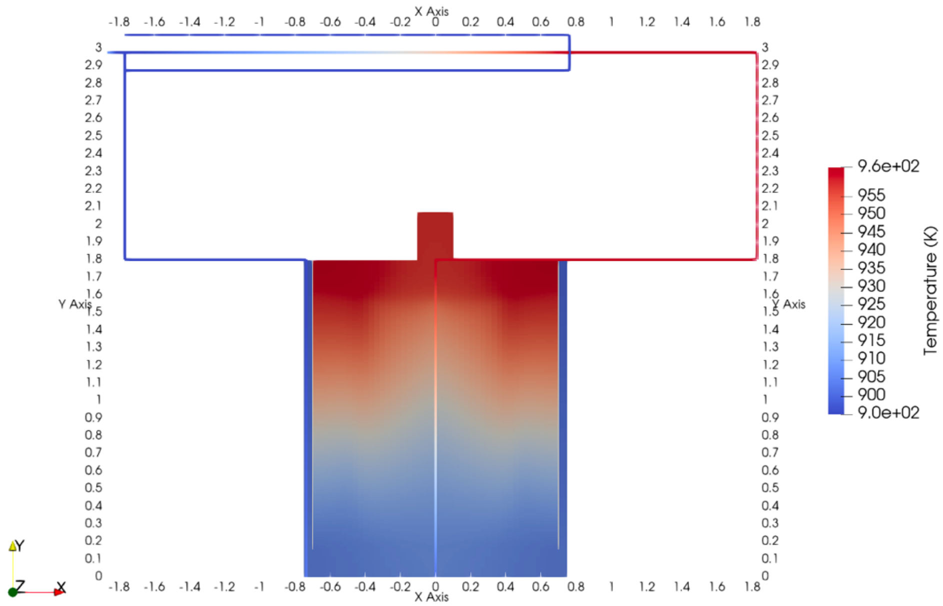


Figure 7. Coupled Pronghorn-SAM thermal-hydraulics result showcases the temperature distribution (K) for steady-state primary circuit and secondary cooling of MSRE. [2]

3.2 High-Temperature Gas-cooled Reactors (HTGR)

Several high-temperature gas reactor (HTGR) models are already hosted in the VTB as seen in Table 1, with several variations represented. New additions were made to the PBMR model [3] and the High Temperature Test Facility (HTTF) benchmark [4] specifically. Additionally, new fuel performance analyses for Tri-stuctural ISOtropic (TRISO) particle fuel using Bison were also added, [5] as well as a pulsed low enriched uranium (LEU) fuel performance model analogous to the Transient Reactor Test Facility (TREAT) reactor. [6]

3.2.1 Pebble Bed Modular Reactor (PBMR)

A SAM-based model of the PBMR-400 was uploaded to the VTB. As in the new MSFR use case, it can be used to compare against existing Griffin-Pronghorn models of the reactor designs on the VTB as shown in the transient response of Figure 8.

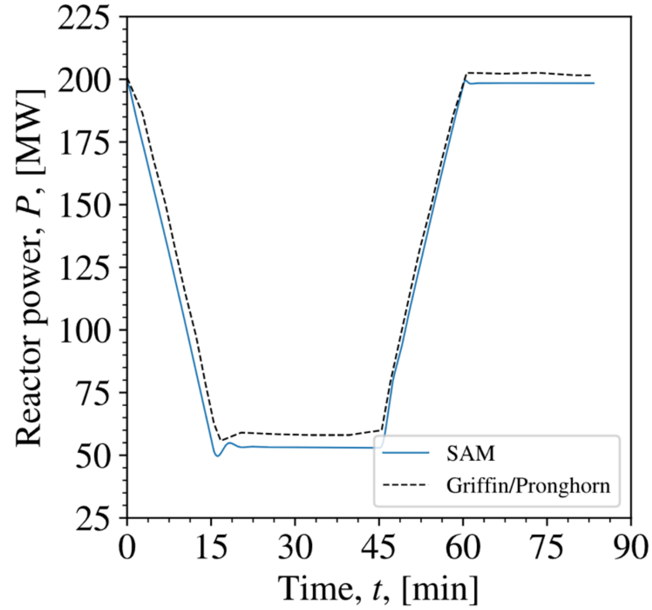
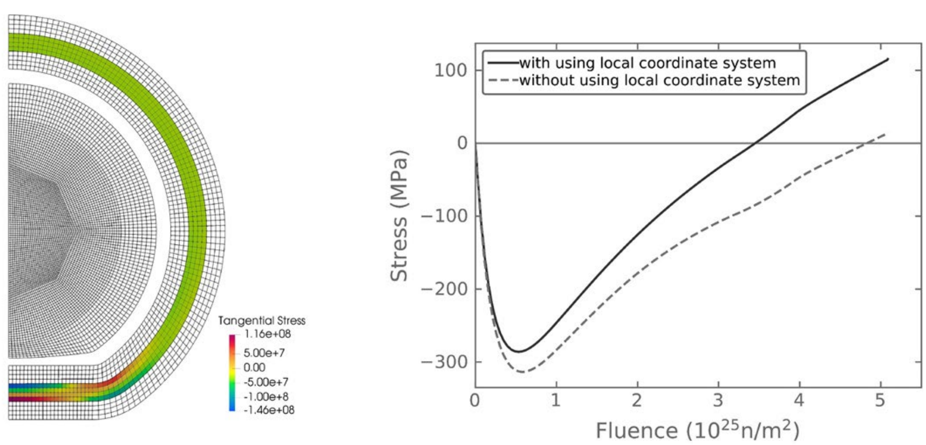


Figure 8. Comparison of the new SAM-based model of a pebble bed reactor versus the Griffin Pronghorn higher fidelity model.

3.2.1.1 TRISO Fuel Performance

New 1D and 2D aspherical TRISO models in the fuel performance code Bison were also included recently in the VTB which demonstrate the effect of burnup and the resulting stress on TRISO fuel as seen in Figure 9. [5] These models are helpful since they can be coupled with other VTB reactor models that use TRISO fuel.



(a) Stress contour (Pa) for T = 1300°C at end of irradiation, with an aspect ratio of 1.04. For clarity, only stresses in the SiC layer are shown.

(b) Time history of stress in the faceted portion of the SiC layer. Results obtained with and without using the local normal vectors are shown for comparison.

Figure 9. Axisymmetric model of an aspherical particle, and time-dependent results for that model.

3.2.1.2 High Temperature Test Facility (HTTF)

Several new models of the HTTF benchmark were uploaded to the repository recently This included system models using SAM and the MOOSE thermal-hydraulics module (THM) (shown in Figure 10) as well as high-fidelity CFD simulations using Nek (shown in Figure 11). These models are especially helpful since they use benchmark data to validate these codes capabilities at replicating real world results.

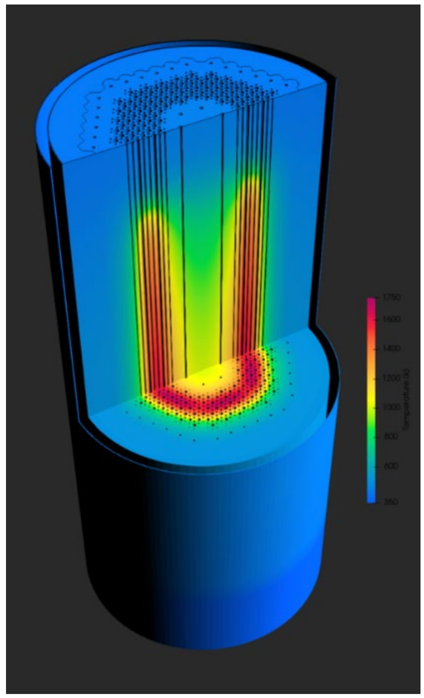


Figure 10. Cutaway of the HTTF model during the hottest point of the PG-26 transient.

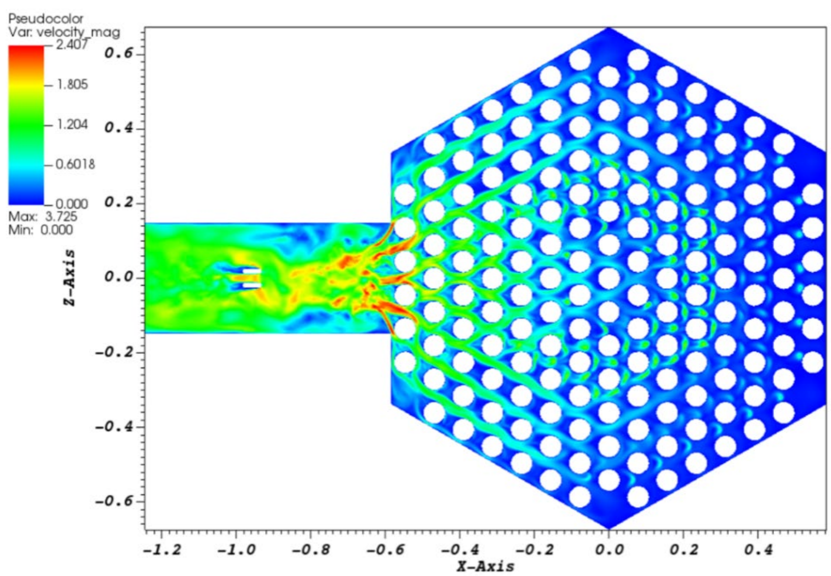


Figure 11. Time-averaged velocity field (non-dimensional) in HTTF lower plenum using Nek.

3.2.1.3 Transient Reactor Test Facility (TREAT)

Last, a multiphysics model of pulsed fuel performance analogous to being irradiated in the TREAT reactor has also been uploaded to the VTB which uses the neutronics code Griffin and the fuel performance code Bison. [6] The results are showcased in Figure 12.

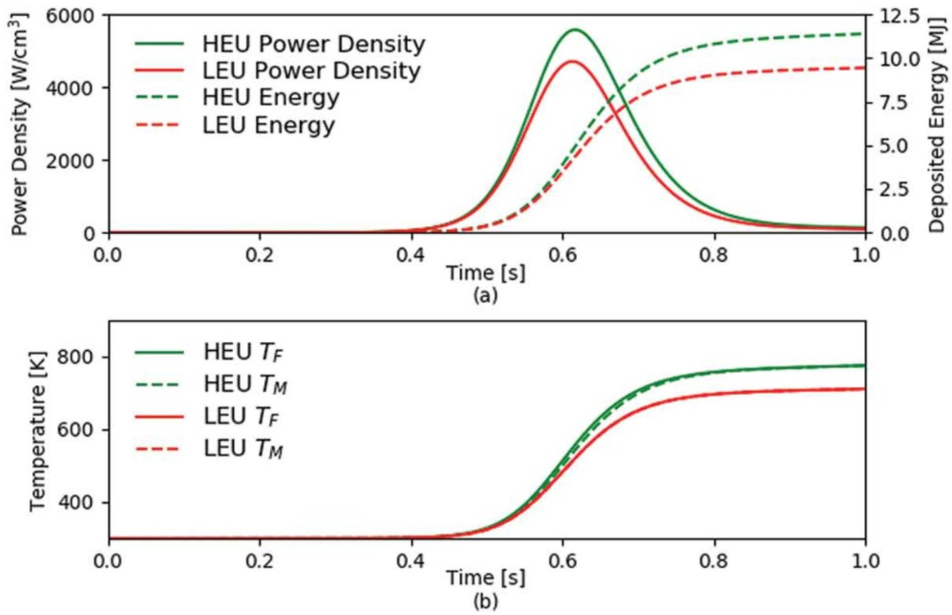
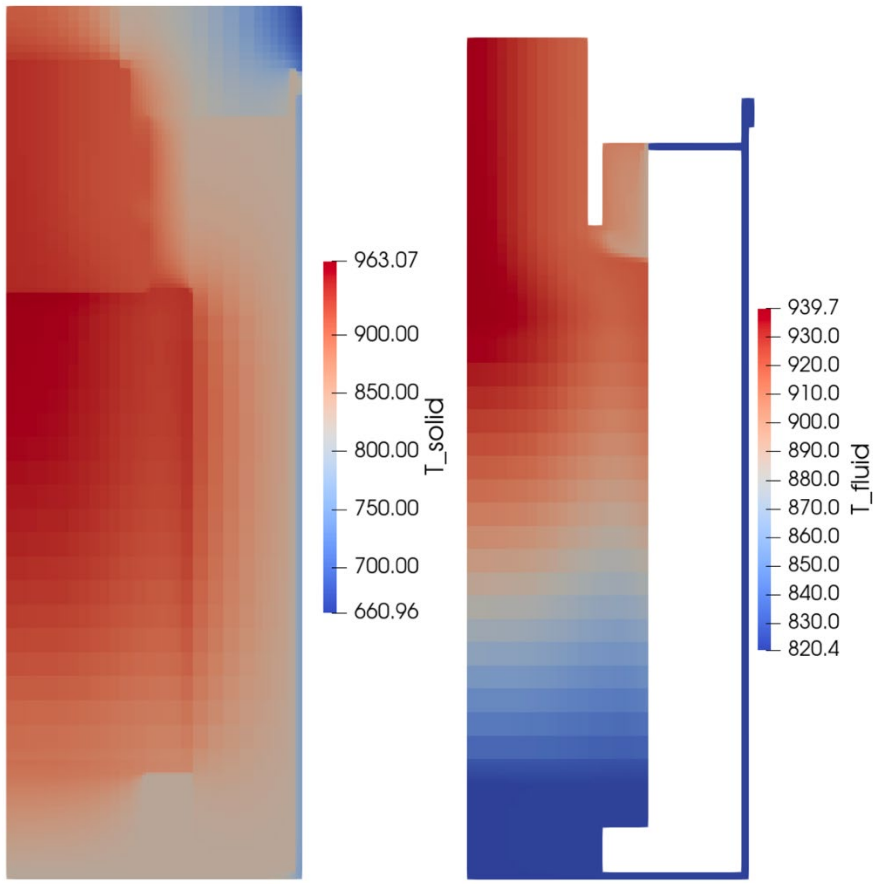


Figure 12. Pulse of matching initial periods for the 10-µm HEU model and the 5-µm LEU model with (a) power density and deposited energy and (b) average feedback temperature results.

3.3 Fluoride High-Temperature Reactors (FHR)

A model showcasing the new equilibrium pebble shuffling in the gFHR model was added to the VTB. The simulation coupled Griffin-Pronghorn to assess the impact of pebble depletion on the temperature distribution in a pebble-bed core. [7] The steady state core thermal solution is shown in Figure 13.



(a) Solid temperature [K] (b) Fluid temperature [K]

Figure 13. Steady-state core thermal solution.

3.4 Liquid Metal Fast Reactors (LMFR)

Three new capabilities for modeling LMFR reactors were recently uploaded to the VTB. This included a detailed heterogeneous neutronics model for a lead-cooled fast reactor assembly [8] (shown in Figure 14), an assembly duct bowing benchmark problem that uses openly available MOOSE modules [9] (shown in Figure 15), and new subchannel benchmarks for LMFR lattices [10] (shown in Figure 16).

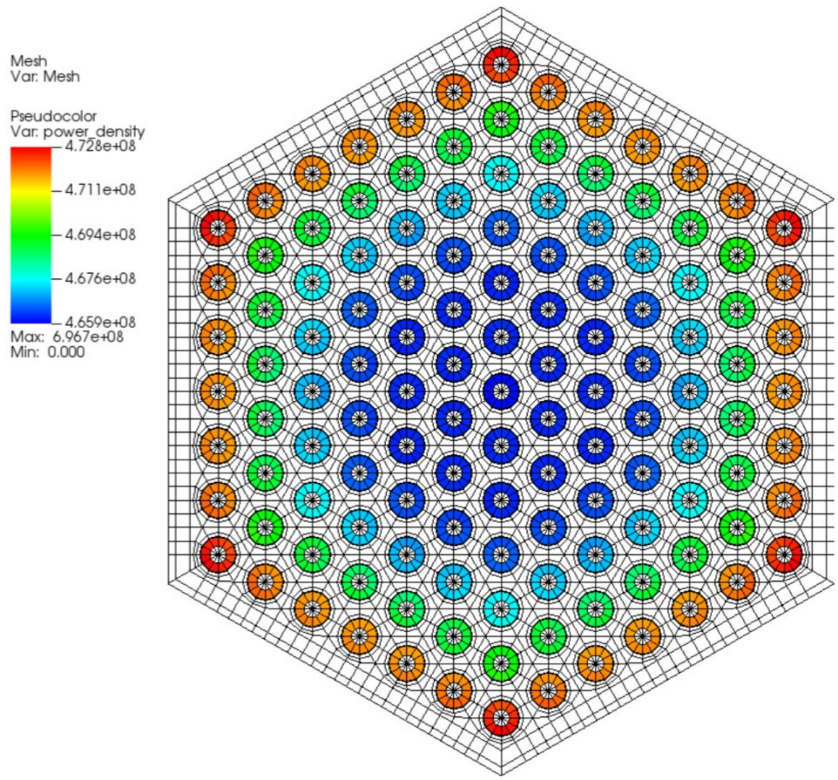


Figure 14. Radial power density profile at the highest axial mesh of the fuel region.

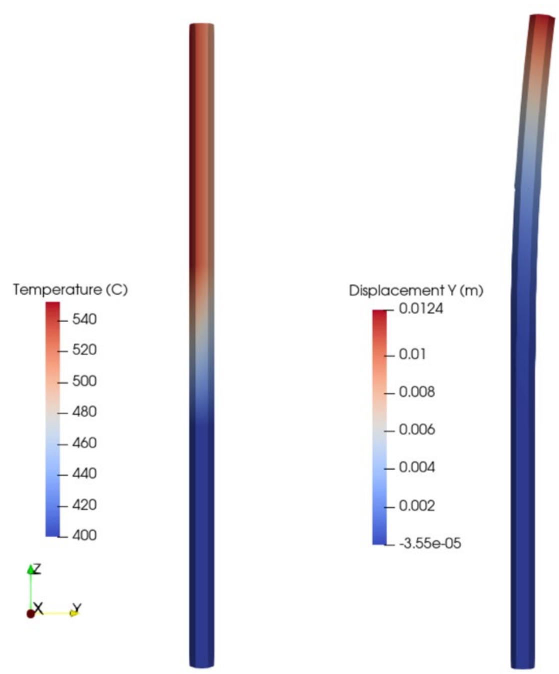
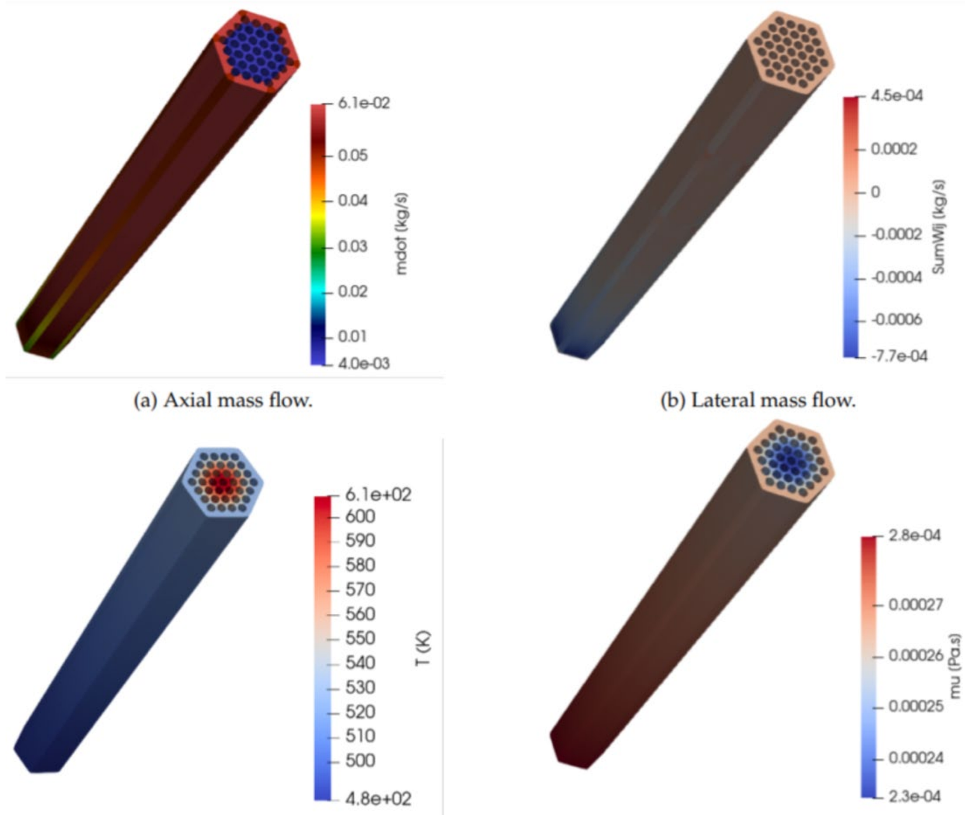


Figure 15. Temperature gradient mapping of the duct (left) and duct bowing (right, magnified) using the MOOSE tensor mechanics module.



(a) Axial mass flow. (b) Lateral mass flow.

(c) Temperature. (d) Dynamic viscosity.

Figure 16. Example of simulation results for the high-flow test case in the Toshiba 37-pin benchmark. (a) Distribution of axial mass flow. (b) Distribution of lateral mass flow. (c) Distribution of temperature. (d) Distribution of dynamic viscosity due to heating.

3.5 Microreactors (MR)

Several new additions were added to showcase microreactor simulation capabilities. These can be broadly grouped between heat-pipe based systems and gas-cooled systems. Last, a Systems for Nuclear Auxiliary Power 8 (SNAP8) reactor model for space use was also developed and uploaded to the VTB.

3.5.1 Heat Pipe

The original heat pipe microreactor model on the VTB was lacking neutronics coupling. The most recent coupling showcases a complete multiphysics simulation including neutronics (Griffin), heat pipe hydraulics (Sockeye), and thermomechanics (Bison). [11] Both steady-state and transient models were uploaded in the VTB. The transient scenario considers a cascading heat pipe failure accident as seen in Figure 17.

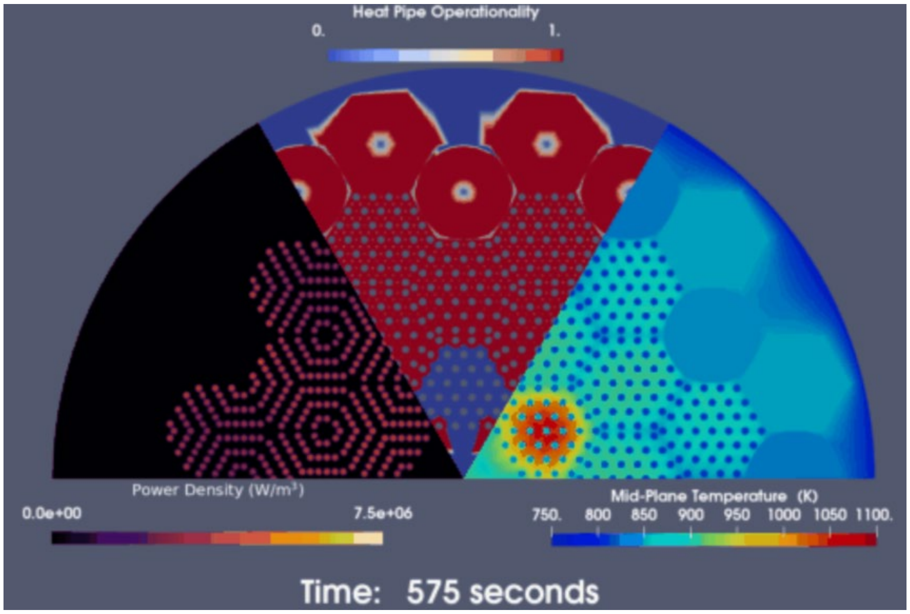


Figure 17. Overview of power and temperature performance of the heat pipe microreactor model on the VTB during a transient.

Additionally, a second heat pipe microreactor model with hydride migration was also included and selected results can be seen in Figure 18. [12] The model is similar to the one above, but captures the feedback that resulted from hydrogen migrating due to temperature and power effects.

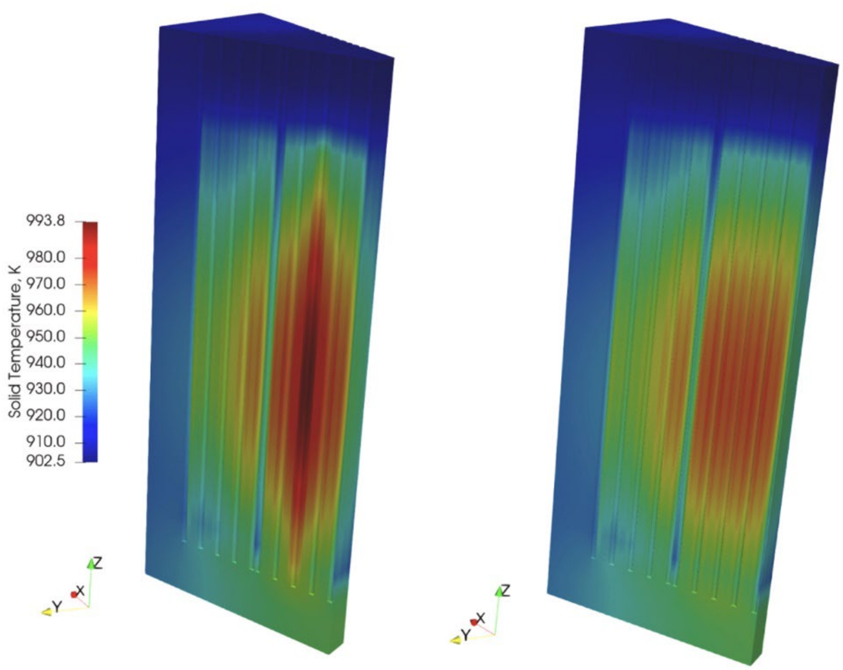


Figure 18. Asymptotic temperature spatial distribution for the heat pipe failure scenario (left) and for normal operations (right).

3.5.1.1 *Gas-Cooled*

The gas-cooled reactor example model on the VTB consists of a 3D assembly model for prismatic HTGR-type reactor but with hydride moderating material as seen in Figure 19. [13] Griffin is leveraged for neutronics, SAM for the system hydraulics, and Bison for the thermomechanics. Steady-state simulations are included alongside transient ones – namely flow blockage and reactivity insertion event.

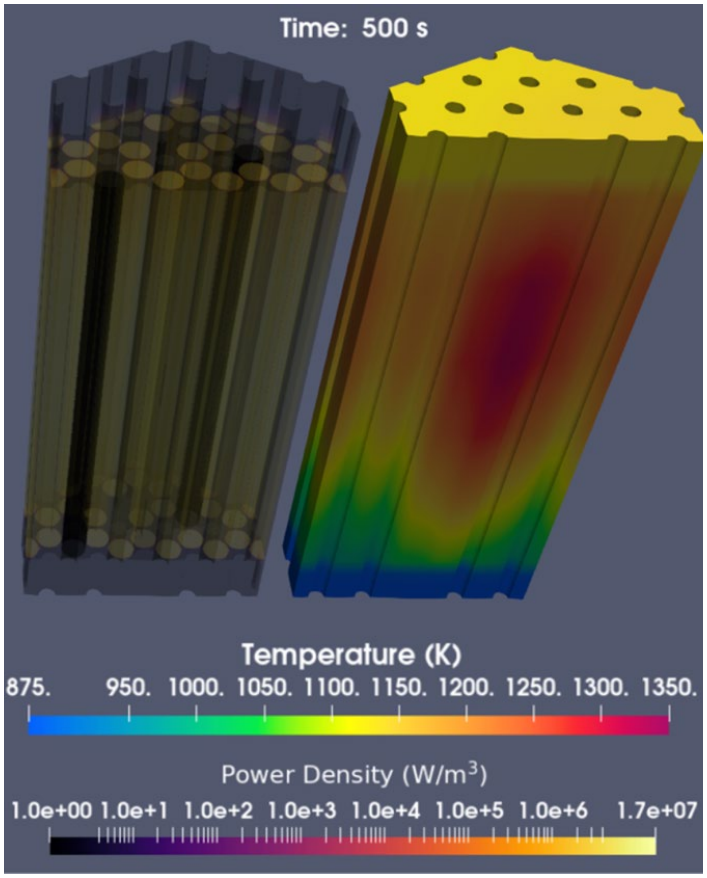


Figure 19. Power density and temperature profiles in the coupled multiphysics gas microreactor model 500 seconds after the transient.

3.5.1.2 *SNAP8 Experimental Reactor (S8ER)*

Last, a multiphysics model of the NaK cooled SNAP8 experimental reactor was also uploaded to the VTB. [14] This model uses Griffin and Bison to solve the neutronics and heat transfer in this legacy micro reactor design. The steady state temperature solution is shown in Figure 20.

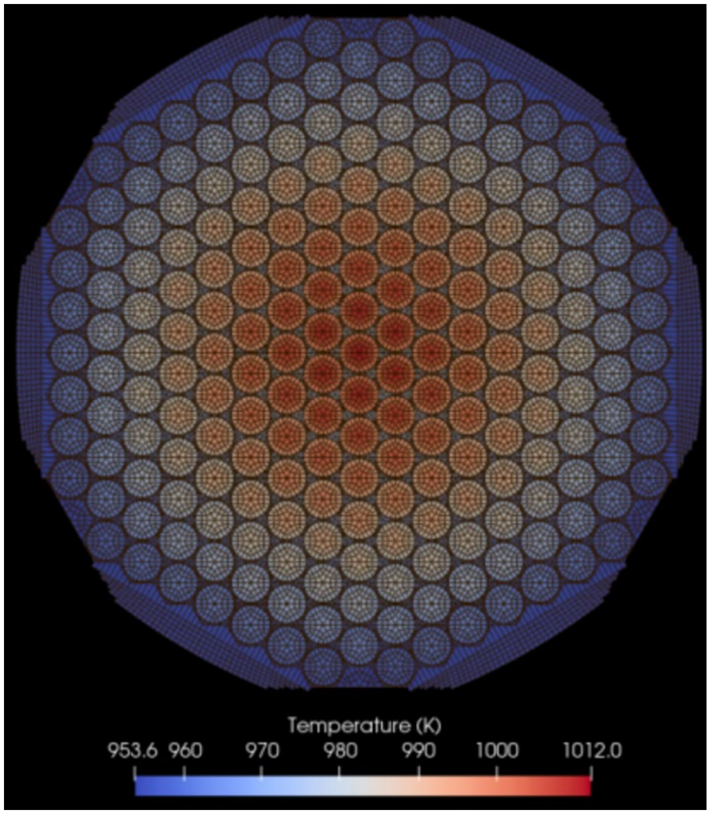


Figure 20. Temperature distribution in the SNAP8 model.

3.6 Upcoming Models Slated for Inclusion on the VTB

Additionally, there are several new models currently under development that are slated to be uploaded to the VTB once the appropriate permissions have been granted. These models are listed in Table 2. They notably include new reactor types like nuclear thermal propulsion (NTP) systems and light water reactor (LWR) models that use NEAMS codes. Additionally, the inclusion of more detailed multiphysics models for each reactor type and new material degradation and aging models utilizing Grizzly will be included.

Table 2. Overview of upcoming reactor models slated to be hosted on the VTB.

Type	Reactor	Simulation	Codes Used
MSR	MSFR	Core thermal hydraulics with NEK5000 informed Turbulence models	Pronghorn; Nek5000
		0D Griffin + Thermochemistry Depletion	Griffin; Thermochimica
		Core steady state chemical species tracking, thermochemistry, and 3D resolved depletion	Griffin; Pronghorn; Thermochimica
	CNRS	CNRS numerical benchmark – steady state neutronics and thermal hydraulics	Griffin; Pronghorn
	MSRE	Core neutronics and thermal hydraulics with system, steady state + transient	Griffin;Pronghorn; SAM
	SILENE	Liquid fuel SILENE multiphysics benchmark	Griffin; Pronghorn

Table 2. (continued).

Type	Reactor	Simulation	Codes Used
HTGR	HTTR	Core neutronics benchmark	Griffin
	PBMR	Updated steady state benchmark and new benchmark transients	Griffin; Pronghorn
	MHTGR	Vessel aging and degradation	Grizzly
	HTR-PM	Steady state neutronics and thermal hydraulics with depletion	Griffin; Pronghorn
	HTR-10	Thermal hydraulics steady state and transients	Griffin; Pronghorn;
	HTTF	Core thermal hydraulics steady-state and transient	Pronghorn
LMFR	Fuel Performance	Metallic Fuel performance	Bison
		UN Fuel performance	Bison
	EBR-II	Subchannel thermal hydraulics	MOOSE THM/Pronghorn
	ABTR	Core heterogenous neutronics	Griffin
		Core neutronics and thermal hydraulics	Griffin; Pronghorn
Micro	Gas Cooled	2D Core neutronics and heat conduction	Griffin; MOOSE
		System level thermal hydraulics	MOOSE THM
NTP	gNTP	NTP system extender cycle model	MOOSE THM
LWR	Fuel Performance	LWR fuel performance	Bison
	Vessel Degradation	Concrete degradation and aging	Grizzly
		Pressure vessel degradation and aging	Grizzly

4. TUTORIAL DEVELOPMENT AND TRAINING ACTIVITIES

Being a host of cutting-edge advanced reactor simulation models, it was quickly realized that user adoption of the tools showcased on the VTB can be expanded with tutorials. The VTB currently contains two tutorials: the first is on the MOOSE MultiApp system that enables multiphysics simulations by transferring data efficiently between codes and the second is on the Workbench interface that can facilitate the setting up and running of problem sets on the INL HPC clusters. Work is underway to include two new sets of tutorials on the VTB: the first is in collaboration with the DOE Advanced Reactor Technology (ART) campaign on how to setup gas-cooled reactor models and the second is on leveraging Bison for fuel performance modeling.

4.1 Existing Tutorials: MultiApp and Workbench

4.1.1 MultiApp Tutorial

Most examples showcased on the VTB leverage several physics that are coupled in various different fashions. As such, it was felt important to include a tutorial on the MOOSE MultiApp system that enables these the types of data transfers. Figure 21 shows the overall hierarchy of how the system organizes different “application,” each containing its separate set of physics.

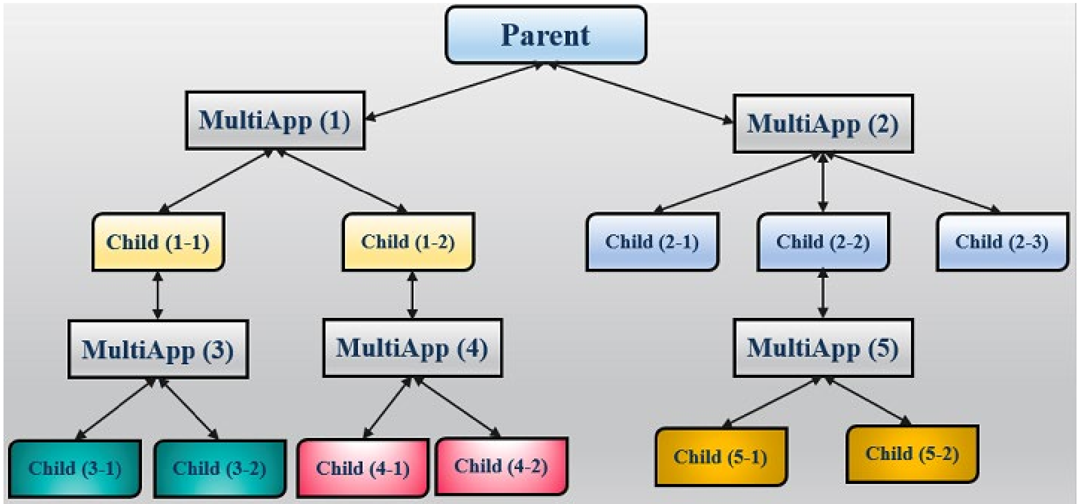


Figure 21. The MOOSE MultiApp hierarchy leveraged in several VTB models.

The application at the top level of the MultiApp hierarchy drives the coupled simulation. This application is termed the parent (or main) application. The parent application can have any number of MultiApp objects. These objects may be added to any individual application to invoke one or more child applications. A child application may then solve completely different physics from the application above it, which may or may not be the parent application depending on its level in the hierarchy. The MultiApp system allows a tree of simulations to be constructed with large numbers of different applications potentially with different time and space scales. Additional information on this tutorial can be found here: https://mooseframework.inl.gov/virtual_test_bed/resources/multiapps.html

4.1.1.1 Workbench Tutorial

Recently, another tutorial was added to the VTB. A tight integration between the NEAMS workbench and the VTB was put in place to enable more seamless execution of simulations. This integration now permits users to easily run VTB examples (or their own models) using the BlueCRAB binary on the INL HPC platform.

The tutorial itself walks new users through cloning the VTB repository, launching a NEAMS workbench session on the INL HPC, running multiphysics examples, and analyzing the results all within the NEAMS workbench Graphical User Interface (GUI). A screenshot explaining the Workbench interface is shown in Figure 22. Additional information on the tutorial can be found here: https://mooseframework.inl.gov/virtual_test_bed/resources/neams-workbench.html

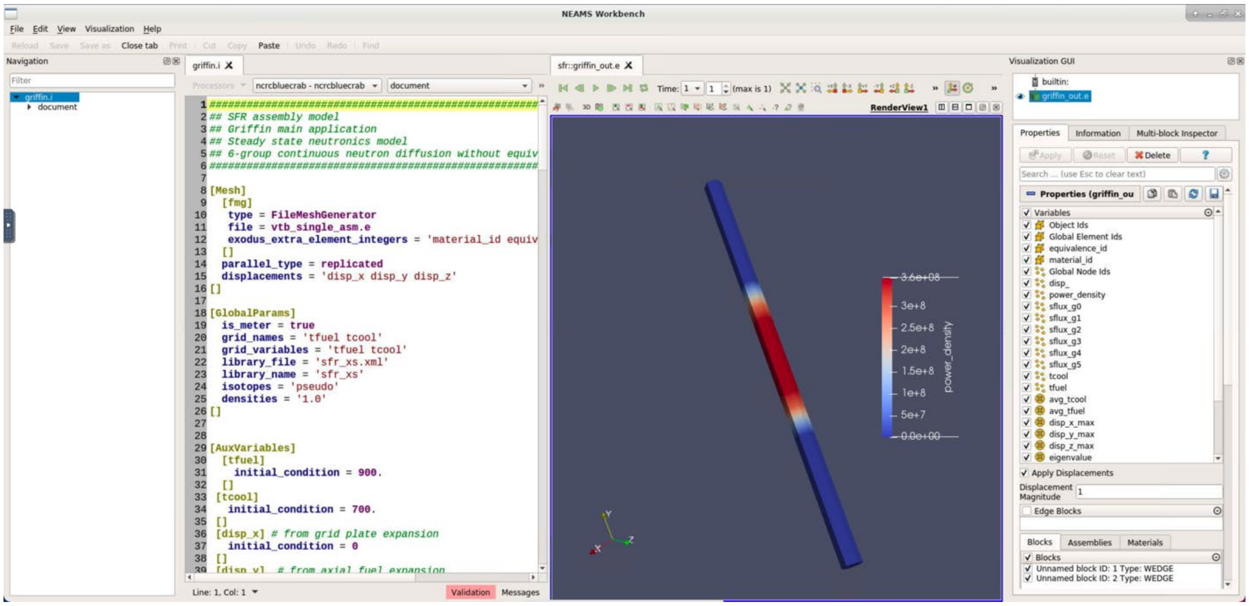


Figure 22. Screenshot of a Workbench interface showcasing a VTB example simulation.

4.2 Pebble Bed Reactor Tutorial

An upcoming tutorial is being prepared for the VTB in collaboration with the ART program. The goal of this pebble bed reactor tutorial is to provide new users of Pronghorn with step-by-step instructions on how to construct gas-cooled pebble reactor thermal-hydraulics models. The tutorial starts out with a channel flow through a porous bed and gradually develops a realistic pebble bed model – a simplified version of the generic PBR (GPBR200) [11] - in about 12 steps. The final exercise is envisioned to tie together the thermal-hydraulics model with the stochastic tools module to perform a sensitivity analysis of maximum fuel temperatures to thermal properties of graphite. The tutorial emphasizes best practices for building Pronghorn models such as checking energy and momentum balances.

The GPBR200 is a 200MW gas-cooled pebble bed reactor based on open-source literature of current and past designs. The geometry of the GPBR200 model in Pronghorn is depicted in Figure 23. The final model in the tutorial will be a slightly simplified version of the GPBR200 model. The difference will be:

- The cone will be removed in favor of a homogenized bottom reflector.
- The discharge chute will not be modeled explicitly.
- The barrel will be omitted and the periphery past the graphite reflector will consist of a single gap and the reactor pressure vessel.

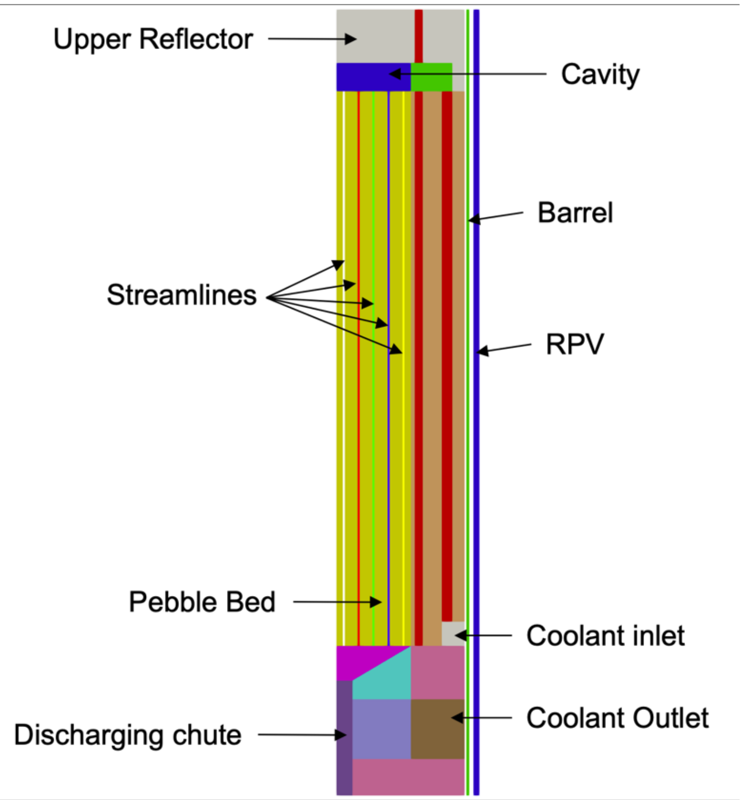


Figure 23. Layout of the GPBR200 model.

The steps to completing the GPBR200 tutorial are listed in Table 3. Most of the steps for the tutorials have been completed and are ready for submission to the VTB. The remaining steps in progress are expected to be completed before the end of the FY.

Table 3. Overview of the Pebble Bed Reactor (PBR) modeling steps in the VTB tutorial.

Step	Description	Status
1	Creation of an axially symmetric flow channel with a uniform porosity of 0.39. No pressure drop or heat source is imposed. Conservation of mass is checked. No temperature equation is solved.	Complete
2	Pressure drop is added to the model created in step 1. The 'KTA' drag correlation is used for that purpose. The expected pressure drop is computed using a hand calculation and using appropriate postprocessors from the code. The values are compared	Complete
3	Equations for solid and fluid temperatures are added. Heat transfer between solid and fluid is added in the bed and a heat source is introduced in the solid in the pebble bed. Conservation of energy is checked.	Complete
4	The geometry is extended to include the cavity above the pebble bed that has a porosity of 1. This introduces a porosity jump in the problem that is treated using Pronghorn's Bernoulli treatment	In progress
5	Top, bottom, and side reflectors are added. The reflectors are the first region where only solid heat conduction is solved.	In progress

Step	Description	Status
6	The riser channel, hot and cold plena, and flow through the bottom reflector are added. Flow now enters the top plenum via the riser channel radially inward and leaves the bottom plenum radially outward. This is the first geometry where the flow is not a channel flow.	Planned
7	The control rod bypass channel in the side reflector is added. The control rod channel is an engineered flow region and is modeled as a porous flow region. The flow branches in the upper cavity from the main flow and merges back in the hot plenum.	Planned
9	Core outer structure including the gaps between reflector and baffle, and baffle and reactor pressure vessel are added. The structures may be simplified from Figure 23.	Planned
10	Steady-state simulation setup. Including post-processing (get average and maximum T solid in the core) and storing initial conditions for transient	Planned
11	Transient simulation (PLOFC) setup and analysis.	Planned
12	Use stochastic tools module to compute sensitivity of bed average and max temperature to graphite thermal conductivity	Planned

4.3 Bison Training Highlighting VTB use and Development

The NEAMS program has committed to submitting fuel performance modeling examples to the NRIC VTB by the end of FY23. Some cases may be added in early FY24. These examples fall under four categories: light water reactor (LWR) fuels, TRISO fuel particles, metallic fuel (U-Zr and U-Pu-Zr), and uranium nitride (UN) fuels.

In the LWR space, two additional examples are planned using state-of-the-art models that have been validated against appropriate experiments in the Bison assessment suite: (1) normal operation to high burnup followed by a loss of coolant accident (LOCA)-like transient and (2) Cr2O3-doped UO2 during normal operation.

For TRISO fuel, a variety of additional examples are planned to demonstrate the versatility of Bison in supporting 1-, 2-, or 3-dimensional analyses depending on the physics of interest. Examples for TRISO will be focused in the two main areas of thermomechanical performance and fission product diffusion.

For metallic fuel, two cases are planned based upon existing Experimental Breeder Reactor (EBR)-II experiments. These experiments will be supported by the EBR-II Fuels Irradiation and Physics Database (FIPD). One will be a binary system of U-Zr and the second will be for ternary U-Pu-Zr fuel. Finally, a single example will be added for UN fuel for demonstrating how to set up a Bison simulation using the latest models. UN development is still in its infancy in Bison and most of the models are empirical in nature.

All examples added will be accompanied by detailed descriptive documentation, Bison models and materials selected for use in the model, the reason for their selection, and their ranges of applicability (i.e., temperature, flux).

5. MODEL DEVELOPMENT ACTIVITIES

Model development activities at the VTB were previously focused on MSR and FHR concepts. Those were previously identified as key gaps in the modeling and simulation space [8] that were not investigated by other programs. As NRIC engages with potential demonstrators, a new priority list was developed in coordination with the leadership team:

1. DOME use case: gas-cooled microreactors
2. LOTUS use case: low-powered MSR

The models were developed in collaboration with ANL. Their activities will be summarized in a separate milestone report. This report will focus primarily on the INL activities.

5.1 DOME Use Case: Gas Microreactor

The model development activities focused on providing examples of high-fidelity core models and incorporating the balance of plant to these models. The balance of plant effects are important for both transient analysis and for normal operation. To this end, the INL activities focused on three different models:

1. Collaborating with the ANL team on the existing gas-cooled microreactor assembly model to include a model using THM, the MOOSE thermal-hydraulics module instead of SAM for the thermal-hydraulics analysis. This will enable this model to be coupled with a direct Brayton cycle using the THM components. An assembly model was provided to the ANL team and will not be discussed in this report.
2. A full balance of plant model using THM using a simplified core.
3. A thermal model of a full core including a subchannel model to assess the bypass flow effects.

5.1.1 Balance of Plant Model

The system is a primary loop with a high-temperature gas-cooled reactor coupled to an open-air Brayton cycle through a heat exchanger. The code used is THM, which is open-source. A diagram of the system is given in Figure 24.

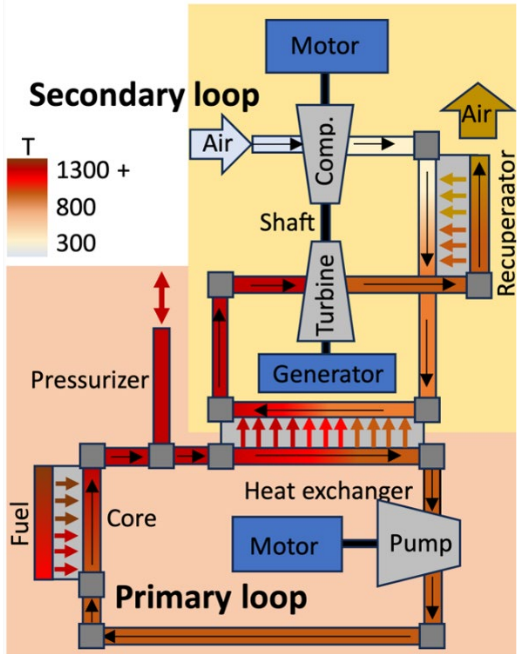


Figure 24. Balance of Plant diagram.

The core design is taken from [15] and consists of 55 hexagonal assemblies, using a graphite matrix, which acts as a moderator. The core is 2 m long, and the sides of the hexagonal assemblies measure 0.11 m. Each assembly has 42 fuel channels of TRISO particles in a graphite matrix and 18 coolant channels. This design uses helium as a coolant. The helium extracts heat from the core and releases it in the heat exchanger. Finally, a pump compensates for the loss of pressure.

The secondary loop is a recuperated open-air Brayton cycle. Air is pumped in the loop by a compressor. It is then heated by the exhaust gases in the recuperator and then in the heat exchanger. The gas goes through a turbine, transfers a part of its residual heat to the recuperator, and is finally released outside. Energy is extracted from the hot air by the turbine to spin the generator shaft and produce electricity. A motor starts the shaft rotation. When the turbine torque is high enough to compensate for the compressor and generator torque, the motor is turned off. The operating conditions are given in Table 4.

Table 4. Operating conditions for the DOME microreactor use case.

Total core power	15 MWth
Primary mass flow rate	9.4 kg/s
Core inlet temperature	890 K
Core outlet temperature	1190 K
Primary system pressure	9MPa
Secondary mass flow rate	20 kg/s
Compressor pressure ratio	8.9
Turbine pressure ratio	2.9
Generator power	2 MWe

For simplicity, the core is modeled using a single flow channel combining all the cooling channels coupled with a representative heat structure. The core power is prescribed as a function of time. The circulator is modeled using the homologous performance curves. A motor is connected to the same shaft and the motor torque is controlled using a Proportional–Integral–Derivative (PID) controller to match the nominal mass flow rate in the loop. On the secondary side, the compressor, turbine, and generator share the same shaft. The performance curves provide the efficiency and pressure ratio as a function of the shaft speed and flow rate. The generator is modeled using a negative torque, proportional to the shaft speed. The torque and inertia of each component connected to the shaft make contributions to the shaft speed equation.

A startup and a load-follow transient were performed. Figure 25 shows the power extracted by the coolant in the core, the power generated and temperature evolution during a startup transient.

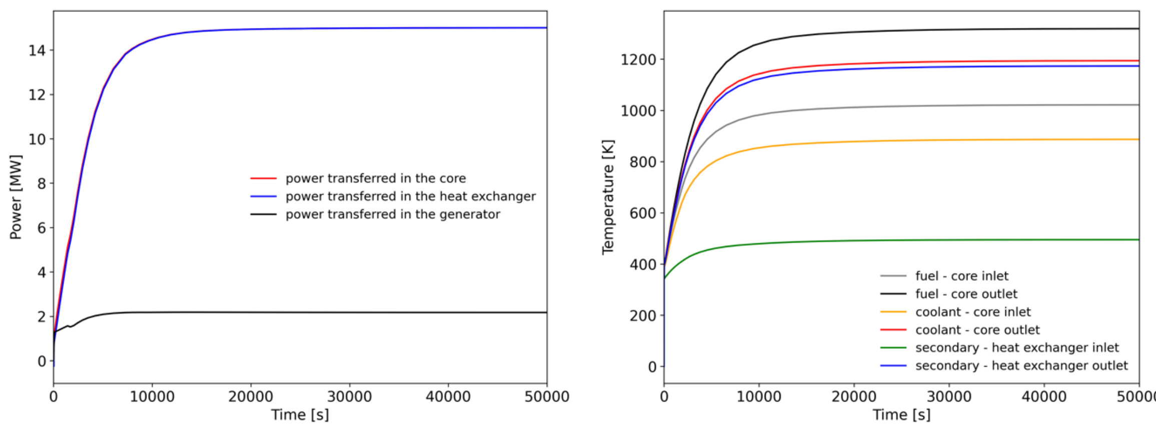


Figure 25. Power and temperature evolution during a startup transient.

The load-follow transient starts from the steady-state conditions, then the reactor power is lowered to 80% of its nominal value, then set back to 100%. Figure 26 shows the resulting powers and temperatures. The power conversion system responds well to the power modulation, and the generated power is 1.6 MW.

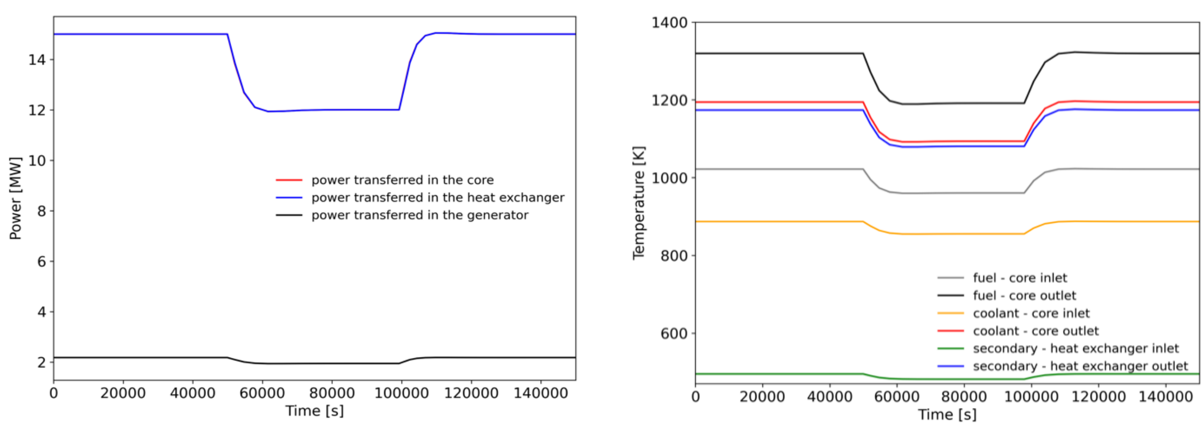
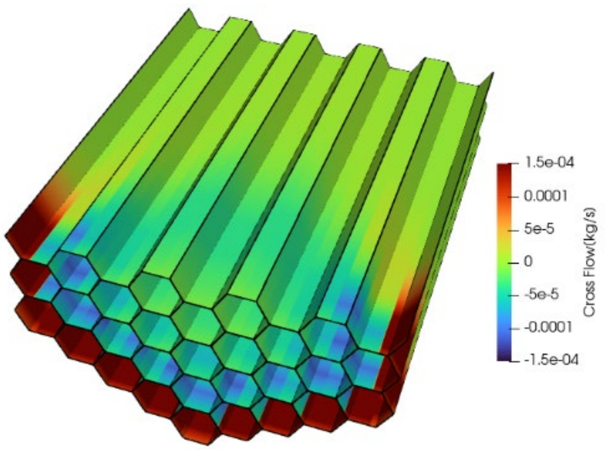


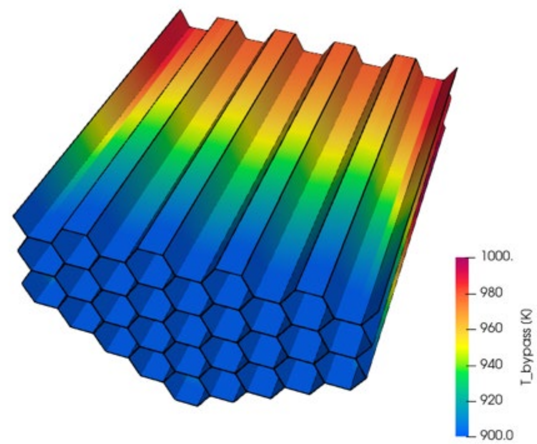
Figure 26. Power and temperature evolution during a load-follow transient.

5.1.2 Full Core with Bypass Flow

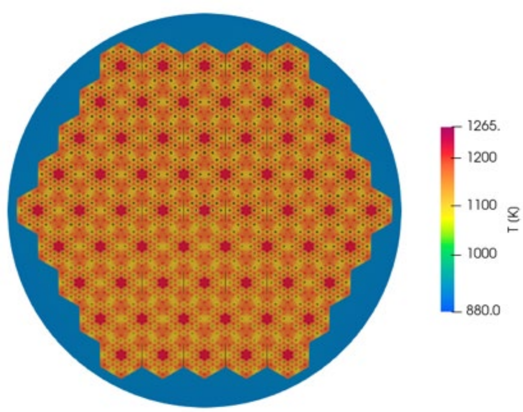
In this model, the core design is similar to the one used for the balance of plant. A detailed mesh of the core was created using the MOOSE reactor module. For compatibility with the Pronghorn Subchannel code, four more assemblies are added on the corners. Gaps for the bypass channels are introduced in the mesh. Power is prescribed in the fuel; the 3D heat conduction problem is solved in the core. The full core model is coupled to the subchannel simulation through a convective boundary condition. It is assumed that 5% of the total coolant flow goes through the bypass. The resulting crossflow in the bypass is shown in Figure 27 with the bypass and core temperatures.



(a) Bypass crossflow



(b) Bypass temperature



(c) Mid-core temperature

Figure 27. Bypass cross flow and temperature in the core and bypass.

5.1.3 Remaining Work

Remaining work includes:

- Develop a model coupling a high-fidelity multiphysics core model with the balance of plant model that was developed this FY.

- Couple the full core model with the Pronghorn Navier-stokes capability to include thermal mixing in the plenum.

5.2 LOTUS Use Case: Low-Powered MSR

The Molten Chloride Reactor Experiment (MCRE) is planned to be demonstrated at LOTUS. Even though this is a low power reactor, a multiphysics model of the reactor was built to ensure the reactor integrity under operational transients and to evaluate sequences potentially leading to accident conditions. The VTB scope intended to demonstrate the capability to model this type of candidate reactor for LOTUS.

The approach integrates a comprehensive 3D multiphysics model, utilizing three key simulation tools: Griffin for neutronics simulations, Pronghorn for thermal-hydraulics simulations, and BISON for thermomechanics simulations. This integration enables the accurate representation of steady-state and transient reactor operations. Behavior of the MSR during a loss of flow accident were also investigated to offer insights into the system's transient response.

This section provides a concise description of the MSR concept studied, an overview of the computational tools employed, and presents results encompassing steady-state operation as well as the response to a loss-of-flow accident.

5.2.1 Reactor Specifications

The proposed design of the open-pool MSR is visually illustrated in Figure 28 and accompanied by a grid indicating the reactor's dimensions. The design specifications were obtained from Reference [16]. The geometry of the model encompasses a primary open core cavity, a pump, and interconnected piping facilitating the flow of the liquid nuclear fuel between the reactor and the pump. Enveloping the main core cavity is a reflector, which plays a crucial role in the reactor's performance.

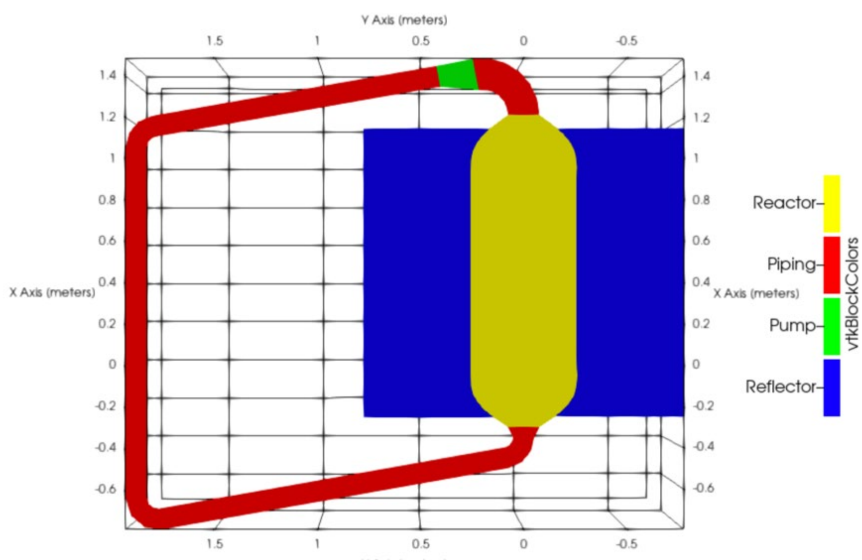


Figure 28. Longitudinal cross section of primary loop modeled for an MCRE-like reactor.

In this MSR configuration, the circulation of the liquid nuclear fuel takes place from the bottom piping, ascending into the reactor cavity, and then flowing into the pump. To counteract the reactivity-temperature coefficient that arises due to thermal expansion, a carefully designed reflector is clamped to the reactor wall. The reflector, currently represented as a solid monolithic block in the model, is expected to be constructed using multiple blocks in practical applications to minimize the impact of thermal deformations and ensure optimal performance.

Notably, the model does not explicitly incorporate control rods, relying instead on normalizing the fission productions using the effective multiplication factor to maintain the reactor at criticality. Additionally, a mixing plate is positioned at the entrance of the reactor cavity to promote uniform flow distribution within the reactor, optimizing the overall operation.

To provide a comprehensive understanding of the MSR design, several key design parameters are outlined in Table 5. The composition of the fuel salt employed in this reactor design is based on the eutectic point of the UCl3-NaCl system, offering specific advantages and characteristics.

It is important to emphasize that, due to the relatively small size of the core, a higher fuel enrichment level fuel is necessary to ensure a sufficiently large reactivity margin above criticality during operation. In its current configuration without control rods inserted, the reactor exhibits a reactivity excess of approximately 12,000 pcm. The mass flow rate within the reactor is regulated at 50 kg/s, resulting in a noticeable pressure drop of 81 kPa across the reactor loop. The fuel salt circulates with an approximate circulation time of 3 seconds, showcasing the dynamic nature of the system.

For a more comprehensive understanding, Table 5 provides detailed thermophysical properties of the fuel salt, enabling a thorough analysis of the reactor's performance and behavior under different operating conditions. Last, it should be noted that the reflector material employed in this design consists of MgO and does not undergo any specific purification processes for its constituent elements, striking a balance between practicality and performance in the overall reactor design.

Table 5. Parameters of modeled LOTUS MSR use case.

Parameter [Unit]	Value
Core Power [MW]	10
Operation Temperature [K]	900
Rated Mass Flow Rate [kg/s]	50
Fuel Salt Composition [mol%]	UCl3 [33.3%] - NaCl [66.7%]
Fuel Enrichment 235U [wt%]	93.2
Salt Density [kg/m3]	$4212.6 - 1.0686\,T$
Specific Heat [J/(kg.K)]	$8900.4 - 13.7\,T$
Thermal Conductivity [W/(m.K)]	$5.682 - 8.783 \times 10^{-3} T$
Dynamic Viscosity [Pa.s]	$1.505 \times 10^{-4}\, e^{\frac{(2.666 \times 10^{4})}{8.314\,T}}$

5.2.2 Computational Codes

The neutronics modeling of the MSR utilizes a diffusion model, implemented with the Griffin computational code. To derive the cross sections and effective parameters for the delay neutron families, data condensation is performed using the Monte Carlo Serpent 2 code, known for its accuracy and reliability in nuclear simulations.

For the comprehensive thermal-hydraulics modeling of the MSR, including the reactor cavity, pump, and connecting piping, the coarse-mesh thermal-hydraulics code Pronghorn is employed. This code enables detailed analysis of the thermal and hydraulic behavior within the reactor system, capturing intricate phenomena and providing valuable insights into the overall performance.

In parallel, the thermomechanics model, responsible for studying the structural behavior and integrity of the reactor reflector, is implemented using the Bison code. By considering the thermomechanical interactions and responses, Bison plays a crucial role in assessing the structural integrity and overall safety of the MSR design.

To ensure seamless integration and efficient interaction among the Griffin, Pronghorn, and Bison codes, the BlueCRAB MOOSE suite is employed. This suite acts as a powerful platform that enables the internal Picard iterations to be performed across all codes, establishing a tight coupling between the different modeling aspects. The integration facilitated by BlueCRAB MOOSE enhances the accuracy and consistency of the simulations, allowing for a comprehensive analysis of the MSR's behavior under various operating conditions.

By combining the capabilities of Griffin, Pronghorn, and Bison within the BlueCRAB MOOSE suite, this modeling approach provides a robust framework for studying the neutronics, thermal-hydraulics, and thermomechanics aspects of the MSR system. It enables a holistic understanding of the MCRE's performance, contributing to the advanced understanding of the reactor dynamics and safety evaluations.

5.2.3 Steady-State Reactor Operation

The continuous neutronics calculations for the MSR core are performed using the Serpent 2 code. Subsequently, the obtained cross sections are condensed into six energy groups to enable efficient diffusion neutronics modeling in Griffin. To ensure comprehensive coverage, the cross sections are tabulated at 20K intervals within the temperature range of 800 to 1,000 K. For temperature values outside the tabulated points, Griffin internally employs interpolation techniques to estimate the cross sections.

In Figure 29, the computed neutronics spectrum for the reactor core, obtained through Serpent 2, is visualized alongside the six-group discretization represented by colored windows. The process of energy bin optimization aims to minimize errors in reactivity and ensure an accurate representation of the neutron flux shape. As a result, a finer discretization is implemented at higher energies, aligning with the increased neutron flux observed within that energy range.

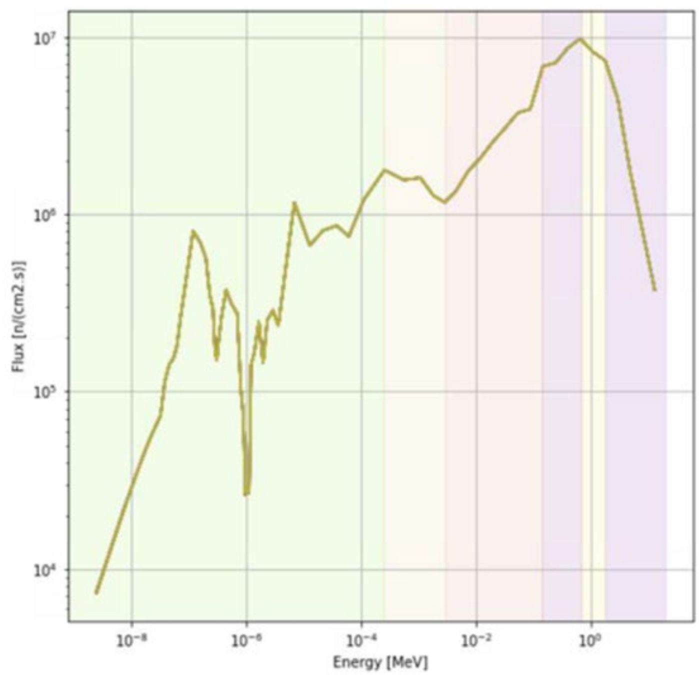


Figure 29. Continuous energy spectrum for MCRE-like reactor core with six-group energy discretization represented in colored bins.

Following the energy bin optimization, a thorough comparison between Griffin and Serpent 2 reference data is conducted. The resulting error in reactivity is determined to be 95 ± 76 pcm across the entire temperature range, reflecting the close agreement between Griffin and the accurate Serpent 2 calculations. Furthermore, the average L2 difference in the neutron flux between Griffin and Serpent 2 results amounts to $0.7\% \pm 0.6\%$. These small discrepancies further demonstrate the reliability and accuracy of the Griffin diffusion neutronics model in capturing the behavior of the MSR across a wide range of temperatures.

By utilizing the advanced capabilities of Serpent 2 and the tailored discretization approach in Griffin, this comprehensive analysis ensures precise and reliable neutronics calculations for the MSR. The close agreement between Griffin and Serpent 2 data in terms of reactivity and neutron flux attests to the robustness of the modeling methodology, laying a solid foundation for further investigations and optimizations in MSR design and operation.

Figure 30 showcases the computed fast-most flux (group 1) and thermal-most flux (group 6) obtained from the Griffin neutronics model. As expected, the fast flux demonstrates a considerable amount of leakage, while the thermal flux diffuses into the reactor's reflector region. Furthermore, Figure 30 includes the collision track plot, a continuous energy neutron flux estimator computed by Serpent 2. Qualitatively, the predicted flux shape closely resembles the fast flux due to the predominantly fast neutron characteristics of the neutron spectrum in the reactor.

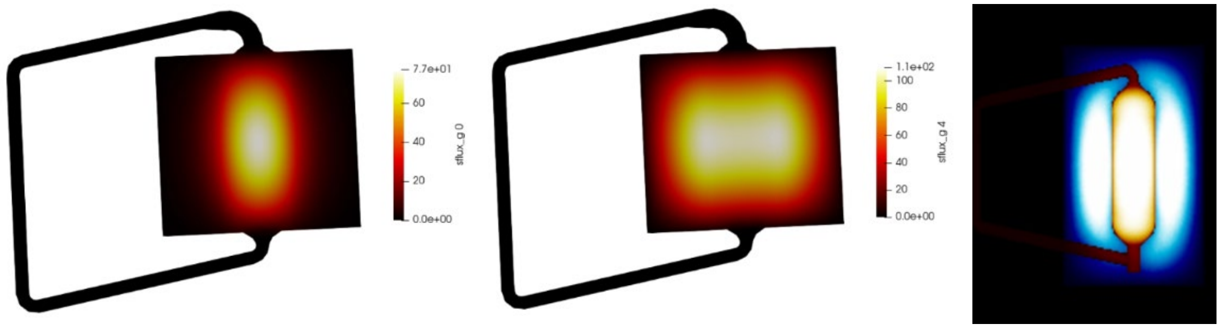


Figure 30. Neutron flux distribution computed by Griffin for the fast-most spectrum (left) and second-most-thermal spectrum (center), and continuous energy collision track plot (right).

The power distribution within the reactor core cavity exhibits a concentration toward its central region. It is important to highlight that these neutronics results have already incorporated the feedback effects arising from temperature, density, and advection of delayed neutron precursors. These feedback effects are accurately computed using the Pronghorn thermal-hydraulics code, enabling a comprehensive analysis of the interplay between neutronics and thermal-hydraulics phenomena within the MSR system.

The visualization of the computed fluxes and the inclusion of the collision track plot provide valuable insights into the behavior and characteristics of neutron transport within the MSR. The concentration of power in the central region of the core cavity highlights the significance of optimizing the design and placement of control mechanisms and safety features. These results combined with the integration of thermal-hydraulics feedback, contribute to a more comprehensive understanding of the MSR's performance, facilitating the development of safer and more efficient reactor designs.

The power distribution obtained from the neutronics model is transferred to the Pronghorn thermal-hydraulics model, leading to results showcased in Figure 31. This figure presents the vertical velocity distribution and temperature profile within the reactor cavity.

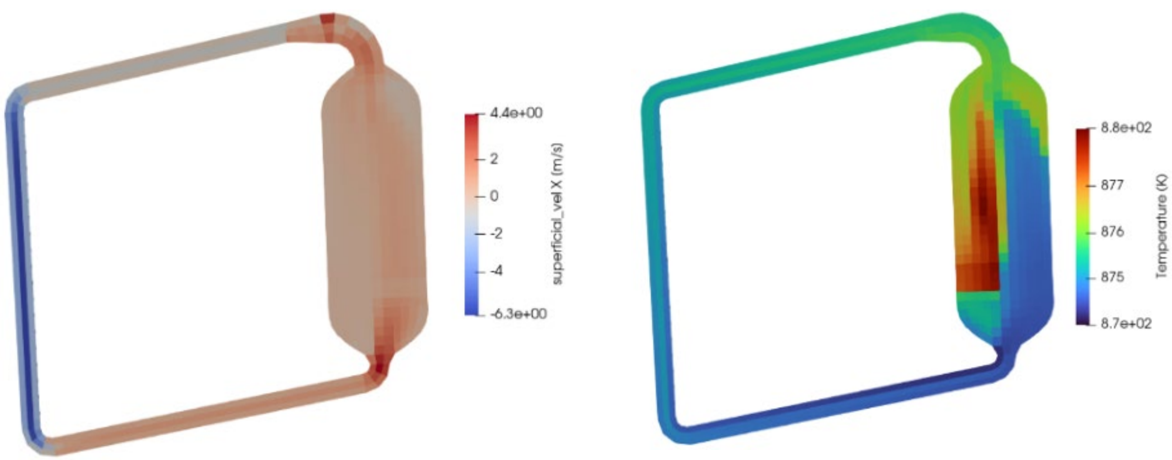


Figure 31. Thermal hydraulics fields steady-state operation of MCRE including fuel salt velocity in the vertical direction (left) and temperature field (right). Note that while the temperature variations may appear to be substantial, they only represent a variation within 10 K.

The vertical velocity field demonstrates the downward movement of the liquid nuclear fuel as it enters the reactor through the bottom pipe, following the flow path indicated by the outermost pipe. Subsequently, the fuel enters the reactor cavity and undergoes partial equalization upon reaching the lower mixing grid after the expansion of the reactor cavity. However, the current configuration exhibits a higher velocity toward the right side of the reactor cavity due to increased pressure resulting from injection through the bottom pipe. As a result, non-uniform temperature fields are observed (Figure 31), with the right side exhibiting relatively cooler temperatures due to faster fuel circulation, while the left side experiences hotter temperatures due to slower circulation in that region.

Given the large mass flow rate within the reactor and the relatively low thermal power, the overall temperature rise across the core is only 2K. It is worth noting that the pipes not in contact with the neutron reflector are treated as adiabatic in this analysis. In practical implementations, achieving this adiabatic condition is facilitated by insulation and thermal blankets applied to these pipes, effectively minimizing heat exchange with the surroundings and maintaining stable reactor performance.

By examining the vertical velocity and temperature distribution in the reactor cavity, this analysis provides crucial insights into the flow behavior and thermal characteristics of the MSR system. Understanding these factors enables the optimization of reactor design, fuel circulation, and cooling mechanisms, contributing to enhanced safety and performance. Furthermore, the negligible temperature rise across the core highlights the efficient heat transfer and effective temperature control within the MSR.

Conjugated heat transfer is conducted between the reactor core and the surrounding reflector to capture the intricate thermal interactions. The process involves employing Picard iterations to ensure temperature consistency between the thermal-hydraulics and thermomechanics fields at the interface where the reactor and reflector meet.

In the thermal analysis, the reflector is assumed to be cooled through natural convection to the atmosphere via the presence of reflector insulation. The free convection coefficient is set at 3 W/(m2.K), while the external convection temperature is fixed at 300 K to approximate typical ambient conditions.

Figure 32 displays the obtained results for the temperature and von Mises stress distributions within the reflector. Notably, the skewed temperature profile, with higher temperatures toward the top-left side, is consistently maintained in the reflector. Consequently, this non-uniform temperature distribution induces corresponding non-uniform deformation of the reflector, with preferential expansion on the top-left side. The highest stresses are observed internally within the reflector, precisely in the region where it is clamped to the reactor wall.

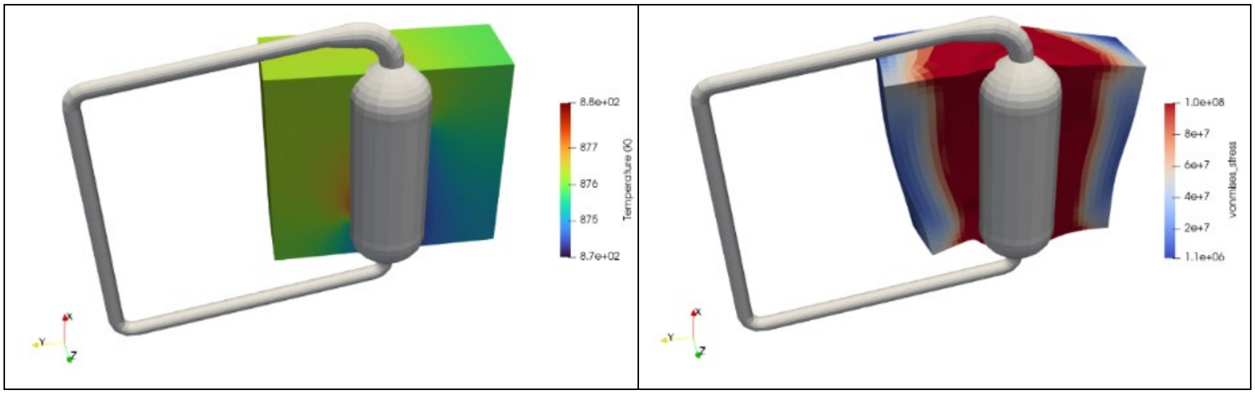


Figure 32. Thermomechanics fields in the nuclear reflector.

Note that, based on the current assumptions and analysis, the reflector is expected to experience plastic deformation in its internal portion where contact with the reactor walls occurs. This plastic deformation is a result of the applied thermal and mechanical loads, emphasizing the significance of considering thermomechanical effects in reactor design and safety assessments.

The feedback of thermomechanics on neutronics must be considered as well. As the reflector expands due to temperature variations, a larger flux of reflected neutrons enters the reactor core, resulting in a positive reactivity-temperature coefficient for the reflector due to thermal expansion. This effect competes with the Doppler effect, which increases neutron absorption in the reflector and leads to a negative reactivity coefficient.

At the operating temperature, the reactivity-temperature feedback coefficient for the reflector is found to be negative, with a value of -5.9 pcm/K. This coefficient is relatively smaller compared to the reactivity-temperature feedback coefficient of the fuel salt, which is determined to be -9.6 pcm/K. The disparity primarily arises from the expansion of the neutron reflector, which is absent in the fuel salt. The additional volume of fuel salt produced by thermal expansion is accommodated in the expansion vessel located outside of the reactor, ensuring the stability and integrity of the overall system.

5.2.4 Loss of Forced-Flow Accident (LOFA)

After investigating the steady-state operation of the Molten Salt Reactor (MSR), an analysis of a LOFA with heater still operational is conducted to assess the reactor's response under such transient conditions. In this scenario, the reactor pump is assumed to initially stop, leading to a rise in temperature within the system. Consequently, the reactor undergoes a transition to a subcritical state, where the power generated within the reactor is primarily derived from residual nuclear heating. Due to the gradual decrease in flow caused by inertia, a small circulation speed is established through natural convection within the reactor. Eventually, a new equilibrium condition is reached after approximately 120 seconds.

Figure 33 illustrates the results of the equilibrium vertical velocity and temperature fields obtained from the LOFA analysis. The control tube at the center of the reactor has been included in the transient model as it plays a role in limiting natural convection. As heat is predominantly lost through thermal conduction to the reactor reflector, the temperature field becomes more uniform, with the influence of temperature convection diminishing. However, it is worth noting that the top part of the reactor core remains hotter than the bottom part due to the gradual heating of the flow as it circulates from the bottom to the top of the reactor.

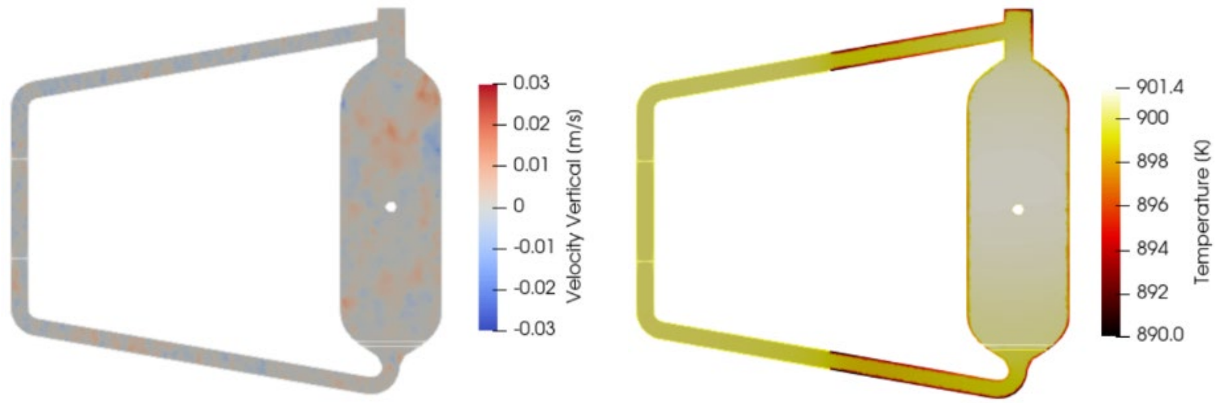


Figure 33. Velocity and temperature fields after 120 seconds of the beginning of the LOFA.

Within the reactor core, the established natural convection gives rise to a few reticulation eddies. On average, a positive vertical circulation speed across the core is observed, indicating the presence of flow motion induced by natural convection. However, it is important to highlight that the average circulation speed within the reactor core is approximately 100 times smaller than the speed observed when the pump was actively promoting flow during normal operation. This decrease in velocity is expected, considering the reactor's relatively low power output and the limited height difference between the hottest and coldest regions within the reactor.

The LOFA analysis provides valuable insights into the behavior and dynamics of the MSR under transient conditions. The observed temperature field and natural convection patterns contribute to understanding the thermal response and heat transfer characteristics during such accidents. By simulating and analyzing LOFA scenarios, engineers and researchers can further optimize safety measures, improve reactor designs, and ensure the integrity and resilience of MSR systems.

5.2.5 Remaining work

Remaining work includes the following:

- Develop a model for thermal-radiation cooling of the nuclear reactor core
- Improve pump modeling in the reactor simulation, which is currently treated as a volumetric momentum source.

6. PUBLICATIONS AND OUTREACH

In an effort to increase the visibility of the VTB, the team held several outreach activities with a wide range of stakeholders. These activities are briefly summarized below. The team had several outreach activities with varying stakeholders listed below:

- Industry presentations: Southern Company, TerraPower-Natrium, TerraPower-MCRE, Westinghouse, Radiant.
- Government outreach: US Nuclear Regulatory Commission, UK Fusion Programmes.
- Universities: Georgia Tech, Massachusetts Institute of Technology, University of Texas Austin.

During FY23, the VTB project outputted several publications both in the form of conferences and journal publications. They are summarized below:

- Two special sessions on the VTB were held at ANS Winter conference in November 2022. This included 10 paper submissions sponsored by the VTB.
- A journal publication on the VTB:
- G. Guidicelli et al., "The Virtual Test (VTB) Repository: A Library of Reference Reactor Models Using NEAMS Tools", Nuclear Science and Engineering, 1-17, DOI: 10.1080/00295639.2022.2142440, (2023)
- The team has also been working diligently on further publications: Another special session at the ANS Winter 2023 meeting on the VTB is being organized (November 2023). Multiple papers have been submitted for the conference and are being reviewed.

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